INTERNATIONAL CENTRE FOR INDOOR ENVIRONMENT AND ENERGY

Energy management in DTU Solar Decathlon house

MASTER THESIS

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FOLD DTU
embrace :: tune :: share

sd europe
SOLAR DECATHLON

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This entire project could not happen without our generous sponsors that provided remarkable service and technologies we would not normally get chance to get encountered with.

Platinum

Gold

Silver

Bronze

Abstract

It would be meaningless to begin with a list of numbers telling how much energy our society uses, how many tons of CO_2 produced every second and try to scare society and hope that everything suddenly change. People will not change anything themselves if they will not really want to. Message of the project, this thesis were part of, was to build an energy efficient, safe, inexpensive and friendly good-looking house that people simply will want.

This project is addresses to student competition Solar Decathlon Europe 2012; an international student competition among universities. The objective is to design and build zero net energy houses that are obtaining all the necessary energy from the SUN.

Key purpose of this Master thesis is to decrease energy use in the DTU competition house and utilize produced energy the most efficient way. The optimal energy solution must be found with a respect both to competition rules but also during the life of the house after competition.

The house has only source of energy; the sun; but there is several ways of energy use that can be combined or replace each other. There often occur a mitchmach between energy demand and supply. The project will optimize energy balance by advising the occupants via live suggestions to utilize directly self-generated energy from renewable sources. Energy performance certification evaluates house as a real zero net energy building.

The energy productive technology in the house is Photovoltaic Thermal system. Team DTU built a unique house for which needed a special roof cover and that was made and built as the self-developed PVT system. Moreover, benefits of PVT according to conventional systems are tested. The junction of electrical and thermal system in one improves the total efficiency even from half the space, compared to the 2 separate systems. PVT establishes positive electrical energy balance with surplus of 79kWh per 12 days. Significant growth of efficiency of electricity generation is caused by cooling the cells to optimal temperature by system of embedded pipes on the backside of photovoltaic panels.

Low-pressure drop of the solar thermal part with Tichelmann connection is using drain back tank system. This combination allows use the system without any chemicals, just with ordinary water and even free of boiling or freezing risk in any climate around the world.

A strong emphasis is paid to innovative and energy efficient Scandinavian design appliances and equipment running on energy. Heating Water Circulation appliances use heat as a main source of energy instead of electricity. This brand new product can save up to 85% of electricity meanwhile the free heat is generated in PVT panels. Functionality is tested in the house built at DTU campus. Experience with operation home systems are utilized during the scored contests and Jury presentations. DTU "home electronics" ended about the lowest energy use level from the entire competition.

Key words: Solar Decathlon Europe, DTU, PVT, HWC, Scandinavian design, Tichelmann connection, low-pressure drop, drain back tank, renewable energy

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Nomenclature

DHW	Domestic hot water
EVA	Ethylene Vinyl Acetate copolymer
E_{task}	Energy used to perform particular task *(Wh)*
$\hat{E}G$	Energy generated by PV system during truncated period (daily 10-17h)
$\hat{E}L$	Energy consumed by el. loads during truncated period (daily 8-23h)
EL	Energy consumed by el. loads during entire day (daily 0-24h)
$\hat{E}B-L$	Electricity exported from batteries to the loads within period (8-23h) in a case of using hard-wired batteries
$\hat{E}G-L$	Electricity generated and simultaneously consumed by the loads within the scored period (10-17h)
FOLD	Official name of the Team DTU´s house for SDE 2012
G	Solar irradiance *(W/m²)*
HWC	Heating water circulation
HP	Heat pump
IEC	International Electrotechnical Commission
IHC	Intelligent home control
K_{tab}	"*Relative*" Power Temperature Coefficient (%/K)
MPP	Maximum power point (maximal power from one string in W, but also way of naming of individual strings)
PPM	Parts per million
P_{roof}	Net expected electrical energy generated from entire PVT area per day, decreased by losses *(kWh/day)*
PV	Photovoltaic
PVT	Photovoltaic thermal
PVT team	Sevela P., Nygaard L., Truelsen F., Borgesen J, Nielsen K., Griguzauskas D.
RPM	Rounds per minute
SDE	Solar Decathlon Europe
STC	Standard testing conditions (irradiance of 1,000 W/m^2, solar spectrum of AM 1.5 and module temperature at 25°C.)
T or Th	Solar thermal
∆T / G	Mean panel temperature-ambient temperature/ irradiation
θ	Incidence angle (°)
α	Absorption (-)
η	Efficiency (-)
ξ	The temporary generation-consumption correlation (-)

1. Introduction

Solar Decathlon Europe is an international competition organized by the Ministry of Housing of the Government of Spain in which universities, which promotes research in the development, build and operate an energetically self-sufficient house, grid-connected but using solar energy as the only source. Houses can be equipped with all of the technologies that permit maximum energy efficiency but on the other hand should inbuilt as few natural resources as possible and produce minimum waste products during their life cycle. During the final phase of the competition, each university team assembles their house in Madrid in Spain, where houses are open to the public, while undergoing the ten contests of the competition, reason for which this event is called Decathlon.

”The competition took place in September 2012, there was 19 houses from 14 different countries, most of which come from Europe (Germany, Denmark, Spain, France, Hungary, Italy, Portugal and Romania) and more from China, Japan, Brazil and Egypt. (*Team DTU, 2012)*

Solar Decathlon is the most multidisciplinary and most advance student competition in the world. The student team members, known as Decathletes, work mostly voluntarily but supported by professors and companies should realize entire process from contacting the sponsors, design of the house to hammer the final nail.

Figure 1- Decathletes of 19 team in Vila Solar

The message of this competition has a second major goal for Denmark and that is the effort to reach the limits given by Denmark' s National Energy Program.

Each house is a pilot program of Zero net energy building that attracted over 200 000 people during 10 days stay in Madrid and even more people followed the story by social media. Idea of Solar Decathlon got to Europe from US and next year China makes own edition. Like a peaceful religion, the idea of Solar Decathlon spreads over the world and tries to influence the people' s mind set about energy use and climate.

Solar Decathlon house is a concepts showing the way for the future move of Denmark to meet target of reduction emissions up to 20 percent by 2020 compared with the 2005 level and moreover fossil fuel independence by 2050 when Coal, Oil and Gas will fully replace Green Energy.

2. Objectives

The objective of this project is to balance and optimize the energy production and energy consumption in the DTU Solar Decathlon House.

This idea appears in several forms:

- Design, evaluation and operation the PV-T system
- Selection and application of low energy appliances
- Relation between time of energy production and energy use,
- Logic that apply human behavior influence to provide energy reduction
- Management of monitoring and testing under competition

3. Solar Decathlon Europe 2012

3.1 The competition

This thesis is dedicated to student project Solar Decathlon Europe 2012. Product of this work was used to perform 3 Jury presentations during competition period in Madrid. Material investigated further in this thesis and related role of team leader was crucial for 6 competition contests out of 10, as seen highlighted on the figure bellow.

No.	Contest/Sub-contest Name	Contests Points	SubContests Points	Assigned by
1	Architecture	120		Jury
2	Engineering & Construction	80		Jury
3	Energy Efficiency	100		Jury
4	Electrical Energy Balance	120		
	4.1 Electricity Autonomy		60	Monitored performance
	4.2 Temporary correlation		40	Monitored performance
	4.3 Electricity use per measurable area		20	Monitored performance
5	Comfort Conditions	120		
	5.1 Temperature		70	Monitored performance
	5.2 Humidity		10	Monitored performance
	5.3 Indoor Air Quality		5	Monitored performance
	5.4 Workstation Lighting		20	Task / Monitored
	5.5 Acoustic		15	Monitored performance
6	House Functioning	120		
	6.1 Refrigerator		5	Monitored performance
	6.2 Freezer		5	Monitored performance
	6.3 Clothes Washer		20	Task + Monitored
	6.4 Clothes Dryer		10	Task Completion
	6.5 Dish Washer		15	Task + Monitored
	6.6 Home Electronics		5	Task + Monitored
	6.7 Oven		15	Task + Monitored
	6.8 Cooking		15	Task Completion
	6.9 Hot Water Draws		20	Task Completion
	6.10 Dinner		10	Guests
7	Communication and Social Awareness	80		Jury
8	Industrialization & Market Viability	80		Jury
9	Innovation	80		Jury
10	Sustainability	100		Jury

Figure 2 Competition contents and points distribution

The SDE contest in total score each team up to 1000 points. Seven of ten contests are evaluated based on opinion of group of three international Juries per contest. Six contests are presented to Juries in half an hour session; the seventh is based on all previous from Innovative point of view. The left three contests are scored according to the monitoring results and results performing specific tasks that simulate living in the house.

In order to be scored for the "Task" and "Monitored" contests a Monitoring plan, Monitoring check list and Monitoring drawings had to be approved. Content of these documents synchronized all monitoring procedures of SDE and project documentation of FOLD house together. Approval of all these document mend that house is ready for safety installation of monitoring equipment. The Monitoring documentation is seen in Appendix G.

3.1.1 Related content

3.1.1.1 *Engineering & Construction*

- Constructive design of the house.
- Plumbing System Design and Construction
- Electrical System Design and Construction
- Photovoltaic System Design and Construction
- Solar Thermal System Design and Construction
- Building Integrated Solar Active Systems

3.1.1.2 *Energy Efficiency*

- Energy analysis of the house and annual consumption estimation
- Efficiency of the appliances and energy saving mechanisms
- Efficiency increase due to the Control System

3.1.1.3 *Innovation*

- innovation concepts in the house's systems' (plumbing, electrical and photovoltaic)
- technological contributions maximizing the energy efficiency of the house
- facilitating the perfect functioning of the house and its equipment

3.1.1.4 *Sustainability*

- minimizing the associated energy consumption to the proposed solution
- degree of local self-supply
- active strategies and systems which improve hydrothermal efficiency
- high efficiency of the electric appliances

3.1.1.5 *Electrical energy balance*

The SDE rules recognize 3 different aspects of evaluation the Electrical energy balance during the competition period in Madrid 17.9.-28.9.2012:

Electricity autonomy

This sub-contest evaluates the electrical energy balance of the competition period; hence two different variables are used:

$\hat{E}G$ Energy generated by PV system during truncated period (daily 10-17h)

EL Energy consumed by el. loads during entire day (daily 0-24h)

Moreover, to be equanimous with all Teams $\hat{E}G$ represents a production of the PV system during truncated period when all houses are free of shadows. This sub-contest was evaluated with full points if the following equation was satisfied:

$$\mathbf{10kWh} \geq \sum \hat{\mathbf{E}}\mathbf{G} - \sum \mathbf{EL} \qquad \text{(Within 17.9. 00: 00 ~ 28.9. 23: 59; 12 days)}$$

Temporary Generation-Consumption Correlation

The aim of this sub-contest is to evaluate standalone behavior of the house. Basically full points are obtained if energy loaded (8-23h) was covered from energy generated by PV (10-17h), or from energy stored in batteries.

Variables are used in this sub-contest:

$\hat{E}G - L$	Electricity generated and simultaneously consumed by the loads within the scored period (10-17h)
$\hat{E}B - L$	Electricity exported from batteries to the loads within period (8-23h) in a case of using hard-wired batteries
$\hat{E}L$	Energy consumed by el. loads during truncated period (daily 8-23h)

The temporary generation-consumption correlation is calculated as follows:

$$\xi = \frac{\hat{E}G-L+\hat{E}B-L}{\hat{E}L} \qquad \text{(Within 17.9. 00: 00 ~ 28.9. 23: 59; 12 days)}$$

Load Consumption per Measurable Area

EL	Sum of daily electrical loads (24h) during the competition
A	Floor area

The load consumption per measurable area is calculated by the following equation:

$$\frac{\sum EL}{A} \qquad \text{(Within 17.9. 00: 00 ~ 28.9. 23: 59; 12 days)}$$

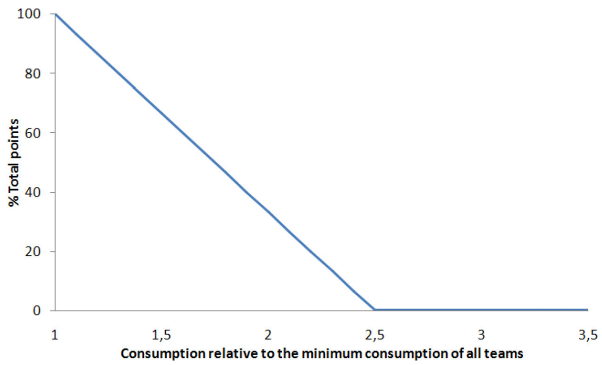


Figure 3 - Evaluation of Load Consumption per Measurable area

For each competition house (18 in total), the load consumption per measurable area is calculated and the points distributed in relation of multiple consumption according to the house with lowest value, see on Figure above.

DTU – Team DTU
19.10.2012

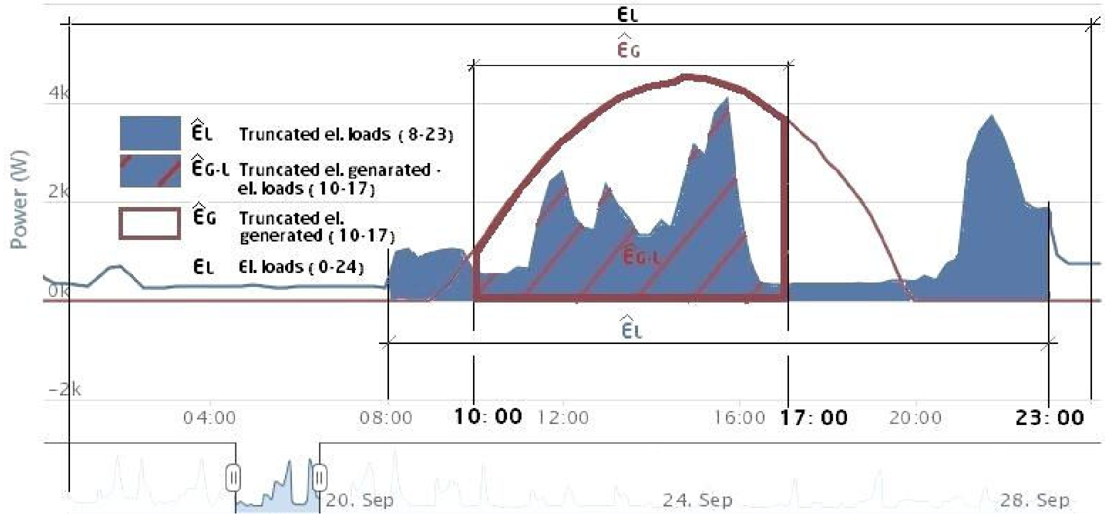


Figure 4 - Example of Electricity flows in FOLD

On the Figure 4 is seen observation of energy flows, (*SDE monitoring site*), during 19th of September. Figure was edited to highlight aforementioned variables, explained also here:

$\hat{E}L$ Energy consumed by el. loads during truncated period (daily 8-23h)

$\hat{E}G-L$ Electricity generated and simultaneously consumed by the loads within the scored period (10-17h)

$\hat{E}G$ Energy generated by PV system during truncated period (daily 10-17h)

EL Energy consumed by el. loads during entire day (daily 0-24h)

3.1.1.6 *House functioning*

Home functioning tasks are evaluated according to the sub-contests rules based on fulfilling certain condition by using electrical energy and consequently influencing the electrical energy balance.

- Clothes washer
- Clothes dryer
- Dishwasher
- Oven
- Hot water draws
- Cooking
- Home Electronics
- Monitored performance scoring
- Refrigerator
- Freezer
- Work station light

Explanation of evaluating conditions and limits for Home functioning are seen in Appendix A.

3.2 The DTU Solar Decathlon house

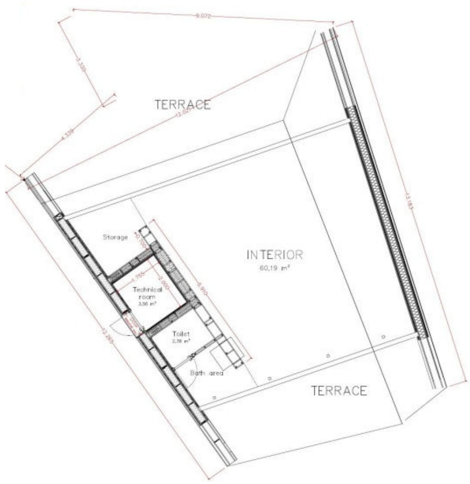
Team DTU participated in the competition with its project named FOLD. This is a plus-energy house, which means that it utilize solar energy both for itself and for the society. FOLD got its name from the architectural concept when piece of paper was folded in a way seen on Figure 5.

The three architectural narratives:

"EMBRACE - embraces solar, biological, economical, ecological and cultural resources of the plot

TUNE - size, inclination and orientation of the different surfaces

SHARE - sustainable living is a collective mindset that engages everybody" *(Team DTU, 2012)*



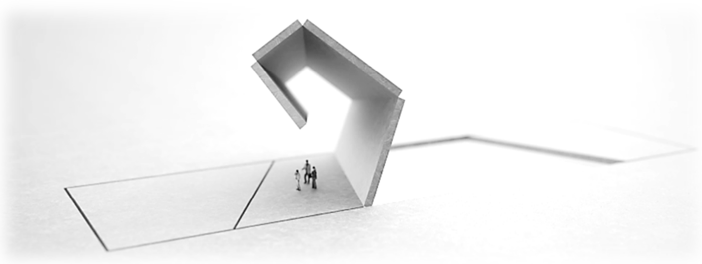


Figure 5 - Fold concept

FOLD is a ground floor house dedicated for permanent living or as a summerhouse for two people. Open space plan merges zone for sleeping, working, dining and cooking. Toilet and bath area are separate. Technical room is accessible from outside what prevents overheating during warm periods. Internal usable area, excluding the technical room, is 66,2 m^2 and in the case favorable weather can be almost doubled by two opposite terraces.

The structural design follows the architectural strategy of thin and light looking skeleton. Wooden elements of walls, floor and ceiling are constructed like stressed-skin panels. The module width of 2.3 m is chosen due to the transportation. Along the house are five modules repeated. All connections are screwed and demountable.

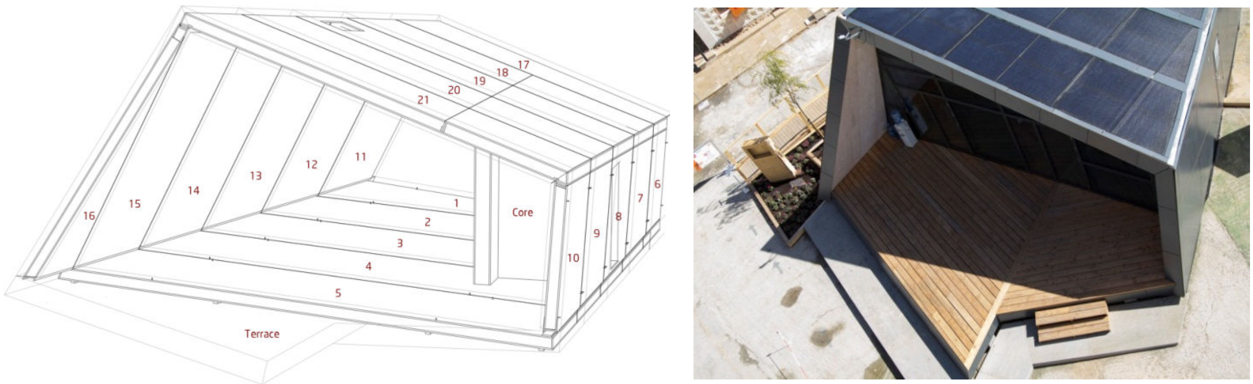


Figure 6 - FOLD skeleton

The highest point of roof is about 5,9 m above the surrounding terrain. Roof overhangs shade two transparent gables made of triple glazed filling. Orientation of FOLD was optimized to facing South-North. In Denmark, the bigger gable faces the South and for Spain was the orientation 180° turned. The market price of FOLD was stated to 2,1million DKK for the prototype.

4. Energy balance

4.1 Energy balance strategy

As can be observed from information above, it has not yet been mentioned any measurement of heat. The competition rules deliberately avoided to this topic and let the teams deal with use of heat productive system by their own.

It was beneficial to replace some of the electrical loads by heat. Thus it was selected to prioritize heat production of the PVT before the electrical production and consider use of heat sources for domestic hot water production, space heating and space cooling and some domestic tasks.

Electrical energy storage (hard-wired batteries) was rejected because from energetic perspective it is loosy way of optimizing the energy balance since the transformation back and forwards between direct and alternating current and since the house is not ever considered to be built as an island system. Certain effort was made to use the electrical car as a temporary battery but this idea was rejected by SDE organization.

According to the conditions mentioned above it was decided to focus on move as much electrical loads to thermal energy and utilize and store the heat preferably due to several orders of magnitude less losses for storing and loading the heat in compare to electricity.

4.2 Primary energy policy in Denmark

"The total primary energy use in the energy frame in Denmark consists of heating, ventilation, cooling, domestic/service hot water, and lighting (except in residences). Electricity consumed by tenants or users is excluded." (*Risto K. and comp. May 5, 2010*)

Danish Energy policy defines coefficients for use (or surplus) of energy on site the following coefficients:

- 2,5 for electricity for buildings fulfilling class 2015
- 0,8 for district heating for buildings fulfilling class 2015

Thus in order to build low energy class building the negative electrical balance very badly influences the Energy Performance Certification.

4.1 Site Energy vs. Source Energy

With the energy policy corresponds the issue of site energy versus source energy. Amount of energy used on-site ("secondary" or "site" energy) does not consider the amount of fuel consumed to generate that primary or "source" energy at a power plant. Therefore were established the energy policy coefficients.

"For example, 2 kW of natural gas burned on-site ("secondary" or "site" energy) for heat might seem more than 1 kW of electricity from grid ("primary" or "source" energy) used on-site to provide the same heat via a heat pump. However, 1 kW of site electricity from the average Danish electrical grid is equal to 2,5 kW of source energy, because of inefficiencies in power plants that burn fuel for electricity, and because of small losses in transmission lines. So in fact the 2 kW of natural gas burned on site is means less for heating." (*Building energy loads, 2011*)

Electricity generated by solar panels on the building includes only primary energy inbuilt during the panel production but do not cause any more primary energy use upstream the source.

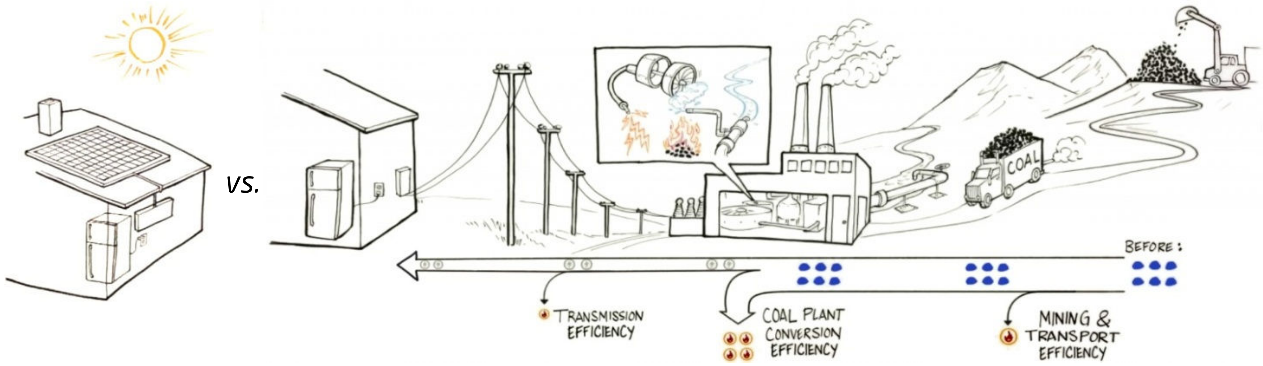


Figure 7 - On-site energy vs Primary energy

Consideration of different sources and self-supply of energy supposed to be part of the early design stage for every building project.

4.2 Energy consumption for domestic use

Nowadays nearly every civil engineer is aware of importance of the insulating the building envelope, efficient way of production heating, cooling and ventilation, lighting and other aspects included in Energy Performance Certification. For the client, real user, of course is important saving of all the resources. No one can expect from the user to deeply understand the complete picture of the energy use in buildings thus the engineers are supposed to go beyond, move focus on other variables of the energy consumption, and give just a solution to the end-user. It is kind of iteration process when a new aspects appears after the rest is pushed down (seen on Figure 8). Now home appliances and human behavior can attract the attention. This topic becomes crucial for design of the net zero energy buildings, like FOLD, where the total energy loads are supposed to be covered by renewable energies.

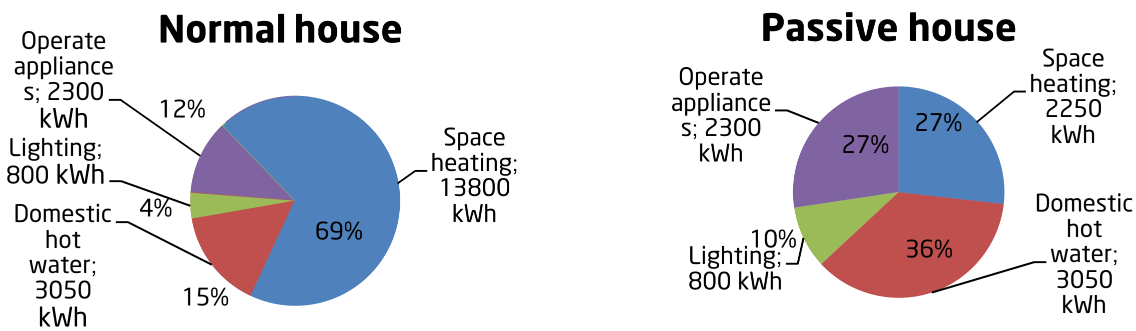


Figure 8 - General enegy ration between Normal and Passive house

The Energy consumption in Danish households; Figure 9; shows that energy spent on performing domestic tasks is significant. People use the energy every minute of their life, even when they sleep. The humans bad habits connected with normal living often create meaningful difference from person to person and then the standards limits consider increased levels.

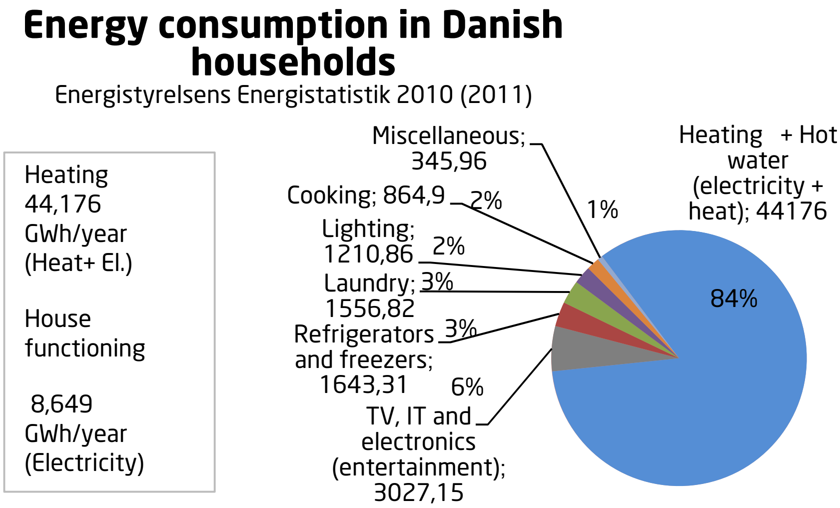


Figure 9 - Energy balance of residential building in Denmark in 2010

The energy consumption for domestic use is also increasing due to higher availability of technologies, which are getting cheaper in compare to the past. Even the technologies are more advanced and appliances are in general more efficient, the energy consumption is increasing. This is another aspect that cause the number of appliances has an increasing tendency.

Survey made in USA showed that the energy consumption for appliances and electronics between years 1978 and 2005 almost double. (U.S. Energy Information Administration, 1978 and 2005 Residential Energy Consumption Survey) .

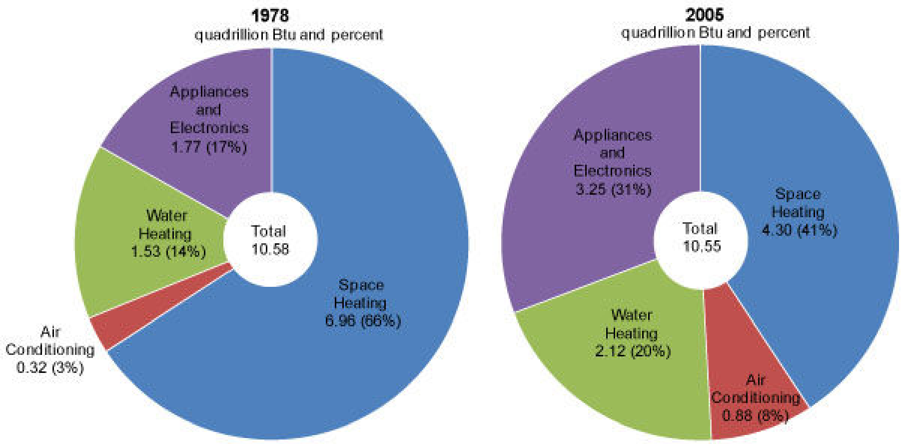


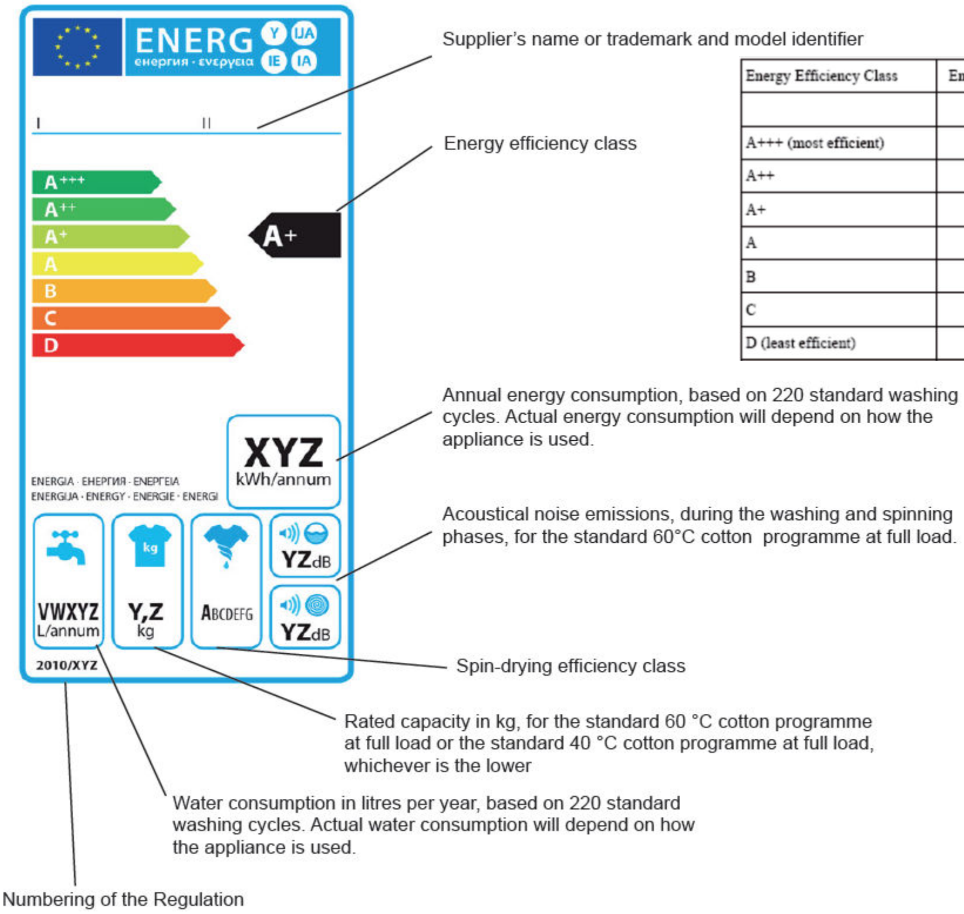
Figure 10 - Energy consumption survey for residential buildings in USA

4.3 Energy labeling

The energy label is a very understandable way to identify energy efficient appliances. Energy labels were first introduced in the EU in the mid 90 years. With the association the EU were then fully implemented. Energy labels allow people interested in buying electrical appliances very quickly navigate between different models of appliances, or their energy efficiency and other parameters. The energy classification for each particular sort of appliance is based on an energy efficiency index (EEI).

Appliances that requires the energy labels from 1 August 2004:

- Automatic washing machines
- Tumble dryer
- Combined washer-driers
- Refrigerators, freezers and their combinations
- Dishwashers
- Electric ovens
- Electric water heaters
- Light sources and Ballasts for fluorescent lighting
- Air Conditioning



Energy Efficiency Class	Energy Efficiency Index
A+++ (most efficient)	$EEI < 46$
A++	$46 \leq EEI < 52$
A+	$52 \leq EEI < 59$
A	$59 \leq EEI < 68$
B	$68 \leq EEI < 77$
C	$77 \leq EEI < 87$
D (least efficient)	$87 \leq EEI < 100$

Figure 11 Example of energy label for washing machines[1]

[1] http: //www.newenergylabel.com/index.php/dk/home/

5. Energy production - Photovoltaic thermal system

High resistance limits efficiency of the conventional photovoltaic systems when high irradiation. The combination of the photovoltaic and thermal system in one is the way to break these limits. PVT is a hybrid system where the thermal part removes the heat, cool down the cells and increases it is el. production with in the same weather conditions. The waste heat from PVT is turned to the yield for hot water production. When the house do not need any more the heat is directed to the heat sink (borehole) and the PVT are cooled even more.

Team of 5 students from DTU (*PVT team*) supported by Danish sponsors and professors developed its own product and brought it to the market. New solution was carried out for mutual connection of panels and piping system. Thermal part with Drain back tank allows replaces typical glycol mixture fluid by normal potable water. This consequence higher thermal performance, more secure functionality and environmentally friendly solution.

The electrical part was designed together with the thermal part. Each electrical string followed thermal zone to maintain as similar temperature for PV cells as possible to provide best conditions for photovoltaic cells. Pretests were used for optimization of the final design that was further tested. PVT system was built in FOLD house, adjusted and control logic was created and tested.

The developed PVT system was compared with Photovoltaic and Thermal systems energetically as well as economically.

During the competition Solar Decathlon Europe 2012 was the PVT system awarded with first price in Solar system integration sub-contest.

"The PVTs were showed as an architecture element with function of the roof top. FOLD house concept very well integrated the PVT system and showed that the solar systems can look nice without any visible machinery around. The entire installations were robust, responsible working and easy to operate. Frame-less panels were appreciated for les maintenance due to the easier self-cleaning property. Well-designed inclination and antireflex glass allowed using the system in different climates and places in the world. Either roof or slanted wall can be used to mount the PVT system. "(Solar system integration juries on Solar Decathlon Europe 2012 in Madrid)

5.1 PVT integration theory

"Approximately 40% of Europe' s energy is consumed in buildings. Provided a significant reduction in energy demand by introducing austerity measures and increased efficiency, solar technologies may become the most important energy source for the building of the future. Buildings have the potential to become active buildings with a 100% solar energy needs covered by sun power in the future, of course, in relation to the development of efficient accumulators of heat and electric energy storage with high density (small volumes)." *esttp.org, 2006*

"This requires that architects and engineers are able to design buildings in the complex approach, combining intelligent architecture, energy efficiency and savings, advanced control of solar gains and innovative solutions for solar systems to ensure maximization the supply of energy." *(Charalambous, 2007)*

"The use of solar energy requires extensive south-facing areas. Striving for rational use of the building envelope for collecting solar energy and conversion to the desired form of energy resulted in the development of active solar elements integrating the equipment into the building." *(Hestnes, 2005)* Great innovative potential still lies especially in the functions of the building envelope and solar collector and multifunctional elements combine several purposes (production of heat and electricity) in a single device. The widespread use of solar energy in buildings is essential to the further development of new concepts and experimental verification of their synergic relationships led to creating easily integrable elements in close contact with the industry for the subsequent commercialization.

Generally used term integration of solar collectors into buildings holds at least three meanings: *system integration*, *architectural integration*, and *structural integration*.

System integration issues concerns how to incorporate solar installations in the energy supply of the building to optimize solar energy gain and coverage. The focus lies in the effective hydraulic and energy concept, design of customized real needs of the building, and advanced control system.

Architectural integration is an important aspect emanating from the experience with a low visual quality of solar collectors installation. Lack of varied palette of colors, shapes, textures and sizes of collectors, visible fasteners and piping are architects most frequently mentioned problems with installing solar systems. While architectural quality is the key to unlocking positive perception of solar collectors by architects and designers and the wider adoption of solar systems by public.

Crucial role can be seen in the integration of solar collectors into structural elements of buildings where solar collectors replace the building envelope. This level of integration is automatically linked to the architectural aspects of integration. Structural form of integration is essential for the future development and expansion of solar technology. Integration of solar collectors into the building envelope instead of separate installations represents the transition from the concept of building envelope energy considered as a loss to the envelope of the building used as a source of energy (energy-active building envelope), which is a step forward towards an active solar energy buildings. Such an understanding of the topic brings new applications like a PVT, solar walls, solar chimneys or Fresnel lens wall.

5.1.1 Hybrid photovoltaic - thermal collectors

Standard solar collectors turns up to 14% of solar radiation into electricity, the rest is waste heat, which partly goes into the surroundings and partly heats the PV module. High electrical resistance caused by overheating of the solar cells thus limits efficiency of the photovoltaic systems. Combination of the photovoltaic and thermal system in one is the way to break these limits. PVT is a hybrid system where the thermal part removes the heat, cools down the cells and increases its electrical production compare to PV within the same outside conditions. The engineering challenge is to cool photovoltaic cells effectively while meaningfully utilize dissipation heat.

„The use of active cooling photovoltaic cells provides low-potential heat and electricity. The heat production can be several times higher than the production of electricity" (Charalambous. *2007)* Thanks to the merged production of electricity and heat (solar cogeneration) in the hybrid collector, total energy output exceeds the energy output from standard separated solutions (solar collectors and PV separately) at the same total built-up area.

Hybrid PV / T collectors can be implemented in several basic variants, as well as glazed or unglazed, flat or concentration and the type of heat transfer fluid air or liquid (Figure 12) (*Matuska,2009)*

Glazed PVT

Glazing with liquid collectors reduces the total heat loss and increases the thermal efficiency compared to unglazed once. Glazed panels can be used to achieve higher levels of temperature (to produce hot water), however at higher operating temperatures, the photovoltaic conversion losses efficiency. Especially in case of stagnation with maximum temperatures of 120 ° C (similar to flat plate collectors) can damage the lamination of photovoltaic cells. Typical EVA laminate withstands temperatures up to 85 ° C, at higher temperatures the material degrades, decomposes and corrosive decomposition products may badly affect the contacts (*Dupeyrat, 2001)*. Generally speaking, the types of glazed collectors PVT have the main function of heat production with the advantage of the current production of electricity from the same area.

Unglazed PVT

The difference according to glazed collectors is that unglazed collectors do not have the lamination of photovoltaic cells and the protective glazing air gap. PVT unglazed collectors have a high heat loss, which can be partially reduced by installing the thermal insulation to the back or integration into the building envelope (the final layer of construction). (*Matuska, 2008)*.

5.1.1.1 *Air PVT*

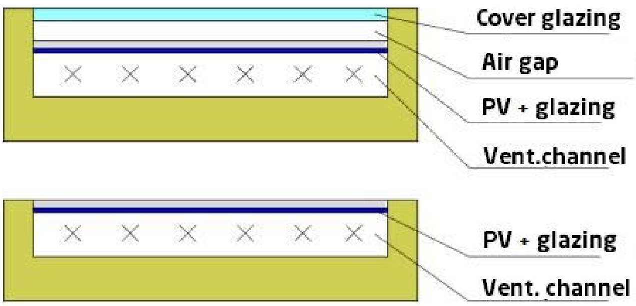


Figure 12 - PV /T air collector (glazed, unglazed)

Hybrid PV / T air systems began primarily as PV facade elements with air channels on the back of the PV module or PV modules placed in a ventilated double facade cavity and have been extensively studied in many demonstration installations. Since systems with natural convection generally did not allow sufficient cooling the PV module, the majority of hybrid PV / T systems use active air circulation. High flow rates required for heat removing due to the low heat capacity of air leads to the large duct size, which is difficult to be integrate into the building structure (envelopes, the inner space). In the case of PV / T systems with active air circulation must also strive to maintain a low consumption of electrical energy required to drive the fans that did not diminish significantly its own electrical energy gain due to cooling the PV cells. The dissipated heat from the PV modules can be used for preheating ventilation air for air heating or radiant heating.

5.1.1.2 *Liquid PVT*

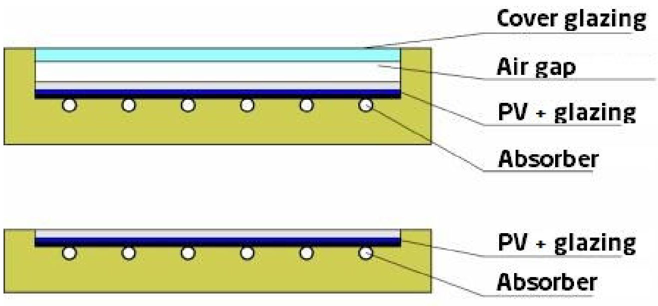


Figure 13 - PV /T liquid collector glazed, unglazed)

Liquid-cooled PV systems are mainly based on the principle of plate-tube heat exchanger (like flat-plate thermal collectors) applied to the back side of a photovoltaic cell or module with superior thermal conductive contact to ensure good heat transmittance. Unglazed design is particularly suitable where electrical power is a major priority and the use of waste heat is an extra. Unglazed PV / T collectors are mostly applied in low-temperature systems, e.g. preheating domestic hot water in buildings, heating pool water or a low potential heat source for heat pumps (absorption PV / T wall or roof). To reduce heat loss and achieve higher thermal performance, especially in periods with low ambient temperatures, it is necessary to use a cover glazing (Figure 13) (*Matuska, 2009)* The thickness of the air gap can be optimized according to expected weather conditions and the required operating temperature. In compare to air PV / T systems applied to many buildings, installation of liquid PV / T systems are still in operation in very limited quantities.

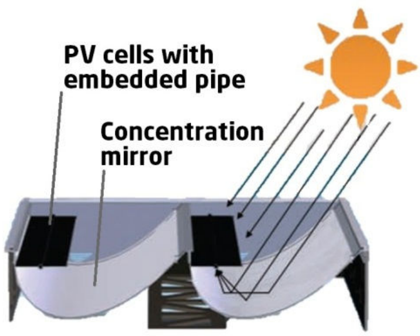


Figure 14 - Example of Concentration liquid PVT

Swedish company Solarus uses MaReCo technology for PVT collectors (aka. Maximum Reflection Concentrator). Technology developed nearly fifteen years ago as a project by accomplished Swedish research institutions and companies including Uppsala and Lund Universities, Vattenfall and the Swedish Energy Agency. *Solarus.se, (2012)*

5.1.1.3 *Air-liquid PVT*

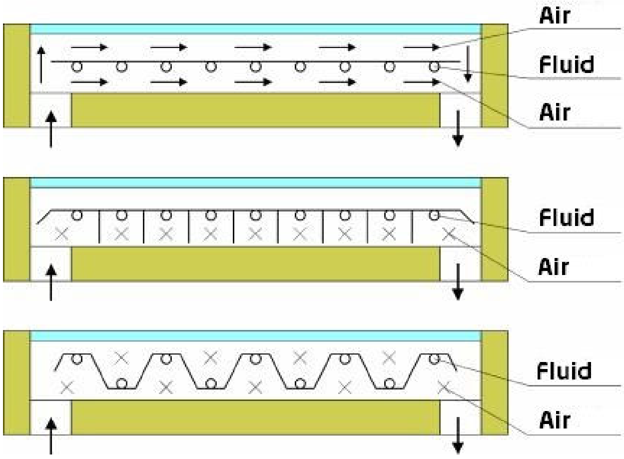


Figure 15 - PV /T hybrid air-liquid collector

„Application of the concept of dual thermal collectors with two heat transfer agents (air / liquid) on hybrid PV / T collectors" *(Tripanagnostopoulos, 2001)* combines the advantages of both concepts and provides a versatile and efficient use of solar energy for the production of multiple ways energy (power and heat) and increase the overall energy gain. (Figure 15) (*Matuska, 2009*) Utilization of heat depends on climatic conditions (e.g. use of air in the winter, use the liquid in the summer), the energy needs of the building (ventilation, hot water, heating), the desired operating temperature of the solar cells, etc. Analogous to the dual thermal collectors, air / liquid, various modes operation for different heat transfer fluid require optimization of dual hybrid PV / T collectors.

5.1.1.4 *Drain back tank system*

Many advantages in compare to standard solar systems bring a not ordinary construction variant of the solar circuit design perspective; Drain-Back system. In idle pump mode the collectors will remain empty, that is when solar radiation is not sufficient to ensure enough heat, power failure, system takes a rest (risk of freezing). The heat transfer medium drains from the collectors into the proportionally large enough reservoir tank, from where the liquid fill the collectors when the pump starts again to circulate. It is therefore a circuit in which, in addition to the heat transfer medium is also a certain amount of air. Such a system has the following features:

Table 1 - Drain back system summary

Advantages	Challenges
• No boiling risk • No freezing problems • No glycol mixtures • Increased thermal performance by about 4% due to use of still water • No thermosyphoning • Inexpensive system	• Skilled designers and installers • Minimal slope of 1% for piping between collectors and drain back tank • Higher pumping head of circulation pump (lifting height) • Not widely used in entire Europe

As a heat transfer fluid can be used pure water, ie. is not required no anti-freeze (water- glycol mixtures).

Because in the collector circuit air plays a role, the system eliminates the air relieve valves.

Preventions thermosiphoning effect when the hot water tank can be discharged in collectors during non-productive period (usually nights). It is caused by rising warm water, with lower density, up to the collectors where lose its temperature and is pushed back to bottom of DHW tank by another hot water. This continues until the circulation force is stronger than pressure drop in piping or the DHW reaches ambient temperature. Drain back system avoids thermosiphoning by the air filling in collectors when system goes off.

The system is very safe because the boiling of the fluid can be prevented by turning off the pump. The same applies to pump failure. The role of an expansion vessel overtakes the drain back tank.

The disadvantage is the possibility of corrosion associated with the presence of air. Since this is a closed system, the risk is manageable, moreover noble materials are used and inert gas filling can be used.

The design and realization phase requires high level of detail due to minimal slope of 1% between solar collectors and drain back tank.

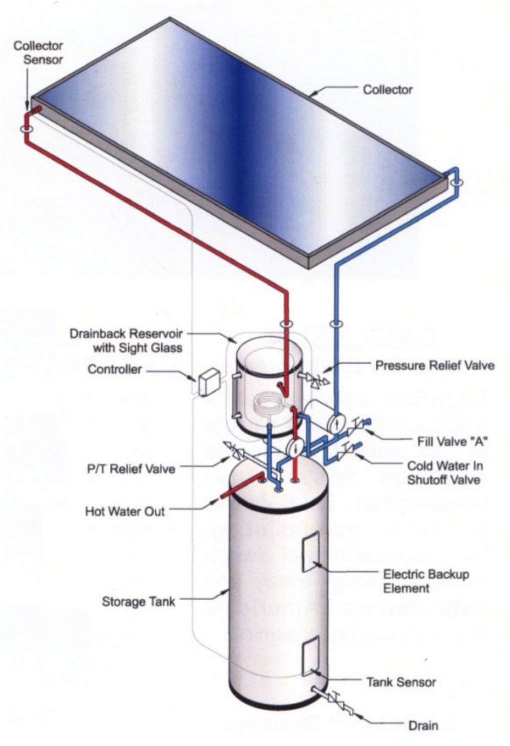


Figure 16 - Drain back system

5.2 PVT development

This chapter includes description of PVT system, design criteria and methods, simulation models and indoor& outdoor measurement of the PVT module. Finally, the system is built and operated; measurements are put into the context wit simulation results.

5.2.1 Design and testing phase

5.2.1.1 *Initial Circumstances*

Photovoltaic thermal system was chosen to be main active renewable source of heat and power for FOLD house. Since the FOLD architectural concept required very thin roofing construction the right large scale PVT ´s was not selected on the market. The decision was made to develop on DTU own large-scale, frameless PVT panels supervised by manufacturer, who claim to have experience with such an installation and did not object to this method of solution. Carpenter company was selected to do build wooden structure of the house and lift and fasten PVT panels to the wooden laths. Mutual electrical connection and wiring was task for company, with knowledge.

Development of the new PVT and related distribution system had to strictly follow required standards:

IEC 60364-7-712	Electrical Installations of Buildings: Requirements for Special Installations or Locations – Solar Photovoltaic power supply systems
IEC 60364	Electrical Installations for Buildings (Installation of PV power supply systems including systems with AC modules)
IEC 61215	Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval. (Manufacturer of custom-made PV panels is obligated to comply with this standard)
IEC 61727	Characteristics of the Utility Interface (Scope: 10 kW or smaller PV systems connected to the low voltage grid)
Royal Decree 1699/2011	Spanish standard which regulates the network connection of electricity production for small power renewable energy and co-generation facilities; allows self-supply of energy (net-metering)
ISO 9806-1: 1994	Test methods for solar collectors (Part 1: Thermal performance of glazed liquid heating collectors including pressure drop)
DS/ENV 13005	Guide to the expression of uncertainty in measurement

5.2.1.2 *Design strategy*

As is previously mentioned in Chapter 5.1 the energy production was supposed to be maximized to cover all energy needs during the year in Madrid, Spain.

Normally is performance of the electrical energy generation system based on the actual energy need but DTU chose the other way around. The PV area same as solar thermal area is designed as big as possible and not with aspect to fit to the Total energy load during a day. Energy surpluses are sold to the electrical grid. In most countries is possible earn money this way and thus decrease the payback time of system installation. DTU system will advise the human behavior to load generated electricity in a hose when is produced, thus electricity purchase will be reduced. This supports the idea of stand-alone system. Moreover, the price ratio is usually unprofitable in comparison between price for selling and buying from the electricity end user point of view.

Due to SDE competition rules it was beneficial to prioritize heat production over the electrical production in term of the construction solution (insulate backside of PVT´s instead ventilated gap) and way of cooling the PVT (priority to DHW tank then to the ground). This does not apply for system functionality after the competition. Than the electrical load for heat pump is not limited and the heat from cooling the cells is usable product but not the desired goal.

Basically the concept was to produce extra electricity by using water to cool down the PVT panels. During cooling of PVT´s the water heated up and that heat was utilized in Domestic Hot Water tank. If the temperature in tank is not height, enough the Heat pump was used to charge the tank to desired level.

When the PVT´s could not contribute to the DHW production any more heat, the PVT´s were cooled in the ground heat exchanger. After the PVT´s gets insulated (AF, 25mm) finally was sustained the control over PV cell temperature and water outlet temperature. The more advanced control logic development became feasible.

The way of contribution of the heat was re-think and it was considered to use heat as main sources for domestic hot water production and some domestic tasks.

The roof construction was, same as walls and floor, across divided into 5 elements due to transportation requirements. Each roof part was 2,3m wide and differently long (6 ~ 8,8m). The roof plane was tilted in two axes, 8 and 16°. Thus, the solution with drain back tank offered itself. This way we could use just water instead of glycol mixtures and thus increase the thermal performance and avoid boiling/ freezing and thermosyphonic effect. On the other hand, the design becomes more complex. The accuracy and proper execution (e.g. min. slope of pipes about 1%) makes the design more challenging.

5.2.1.3 *Mockup #1 and preliminary simulations*

Purpose of this section is to briefly present outcome of indoor & outdoor testing done along the development process of final PVT design. More detailed conditions of carried testing were deeply described in *Borgesen J., Nielsen K.(2012)*.

The very **first** PVT panel was just a mockup (mockup #1) without any PV cells. The manufacturer did entire design. Plastic piping was laminated to the Plexiglas with copper absorber in between. This first panel was leaky from joint between two Alupex pipes as see on Figure 17 (*Borgesen J., Nielsen K.2012)* Mockup was tested on setup created for purpose of this project located on DTU in workshops of building 119.

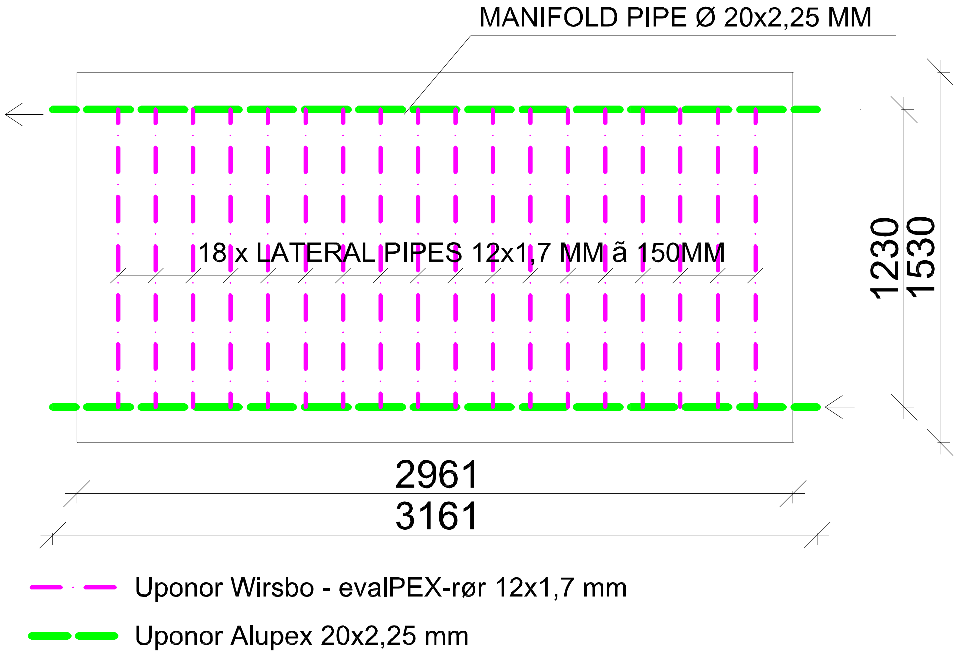


Figure 17 - PVT mockup #1

Investigation of different spacing was running in the meantime. The number of the lateral pipes across the absorber has a large influence on the panel' s ability to transfer heat from the absorber plate and to the liquid. A simulation was conducted to look at the influence of "Fin factor" (part of energy absorbed from outside to absorber with piping.) and "Fin efficiency" (share of energy transferred to fluid inside the pipe) per meter panel.

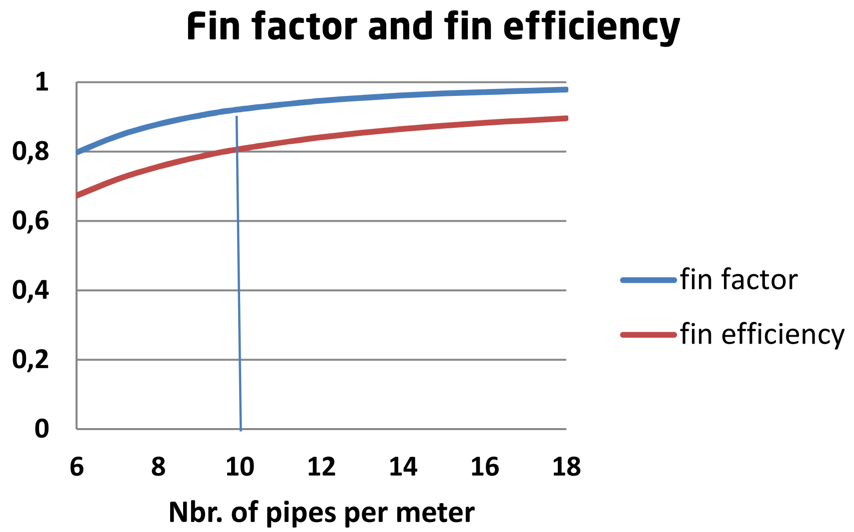


Chart 1 - Fin factor and fin efficiency

On figure (Fin factor) is seen increasing tendency of the fin efficiency with smaller spacing of absorber piping. Around number 10 (10 lateral pipes per meter) the curve flattens and even smaller spacing becomes ineffective.

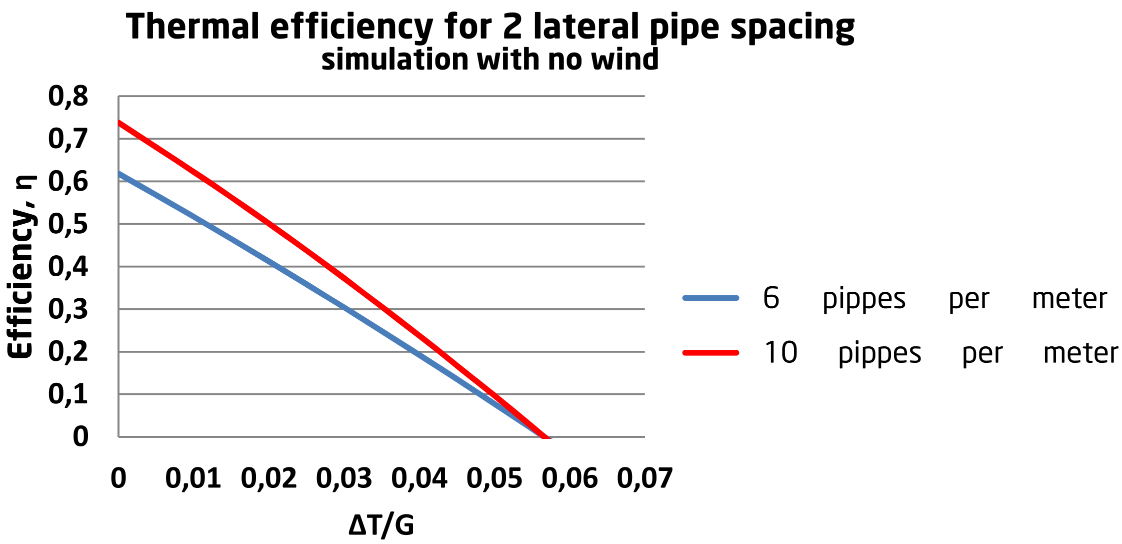


Chart 2 - Thermal efficiency for two lateral pipe spacing

Furthermore, spacing 6 and 10 pipes per meter were investigated. Another simulation was conducted to illustrate the panel´s effectiveness in relation to different numbers of lateral pipes, namely 6 and 10 per meter. From Chart 2 is clearly evident that spacing 100mm has significantly higher efficiency in situation when the temperature difference between surrounding and PVT surface is not significant, thus the heat loss is not dominant. Such a situation is expected as target conditions of the final product.

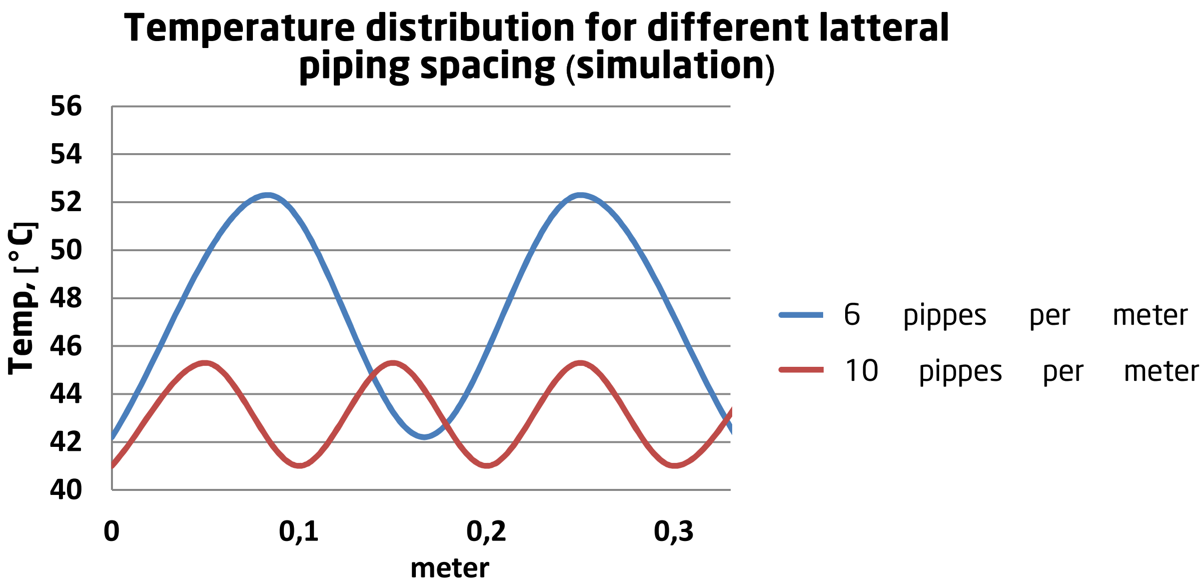


Chart 3 - Temperature distribution in series with different lateral pipe spacing

On graph above is seen temperature distribution across absorber plate for the two spacing. The peaks indicate intermediate space between two pipes where the temperature raises most. It is desired to have the as even temperature over the absorber as possible, thus spacing (100mm) with temperature range of 4K seems more reasonable than spacing (166mm) with temp. range of 10K. Although the production cost might be higher for the smaller spacing, the temperature difference of 10K within 166mm is unsustainable.

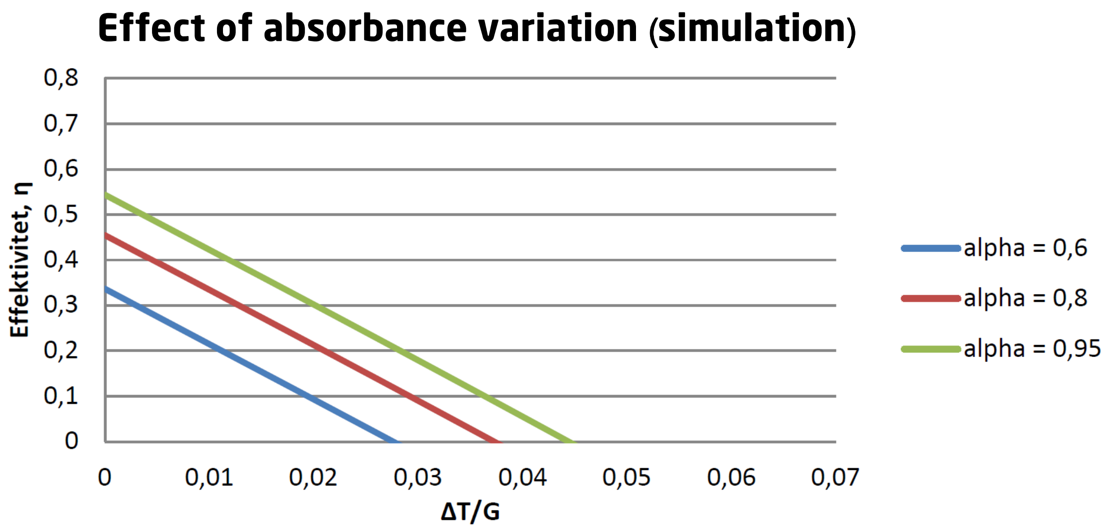


Chart 4- Effect of absorbance variation

Mock-up panel is assumed to have an absorption coefficient equal to tedlar´s, α = 0.94, since this the mockup was only covered by the transparent EVA and glass. When PVT panel is produced with solar cells the absorbance change. It was not possible to ascertain the exact absorption coefficient for the used solar cells, but generally α lies between 0.6 and 0.8. The effect of this change (seen on Chart 4 shows that the absorption coefficient has a crucial importance. It is necessary to know the exact α value in order to make an accurate simulation.

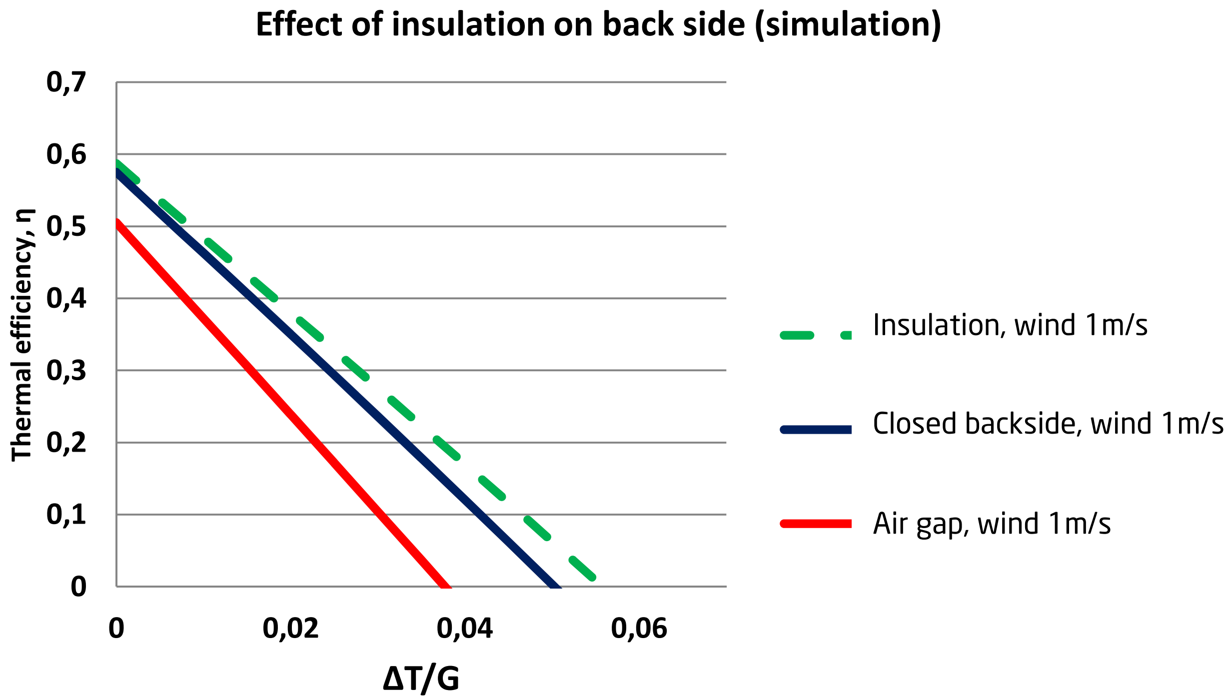


Chart 5 - Effect of insulation on PVT panel back side

A simulation was conducted to see the importance of heat loss and air flowing on the backside of the panel (naturally or due to wind). This simulation was an important argument in design proposals of roof for FOLD house.

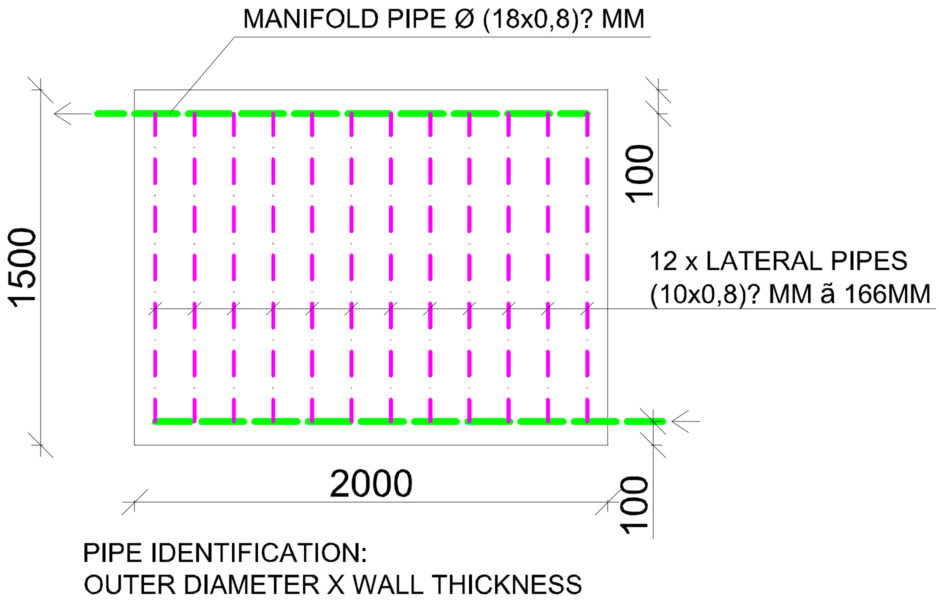
The three variations are explained here :

- Insulated back side : The simulation was performed with 25 mm insulation, thermal conductivity of 0,047 ($W / m \cdot K$) glued on the back side of panel.
- Closed backside : It was assumed a closed air gap of 20 mm at the back of the panel.
- Air gap: The air gap of 20mm was fully ventilated.

Chart 5 shows a significantly improved thermal performance by isolating the back of the panel. According to the concept described in Chapter 5.1 it was decided to insulate the back side in purpose of DHW heating.

5.2.1.4 *Mockup #2 testing and final simulations*

The design of **Second mockup** (mockup#2) was also done by company RAcell even *PVT team* made own proposal for the thermal part. It was used real glass, copper piping and copper absorber. The piping dimensions were not clarified. The setups is seen on Figure 18.



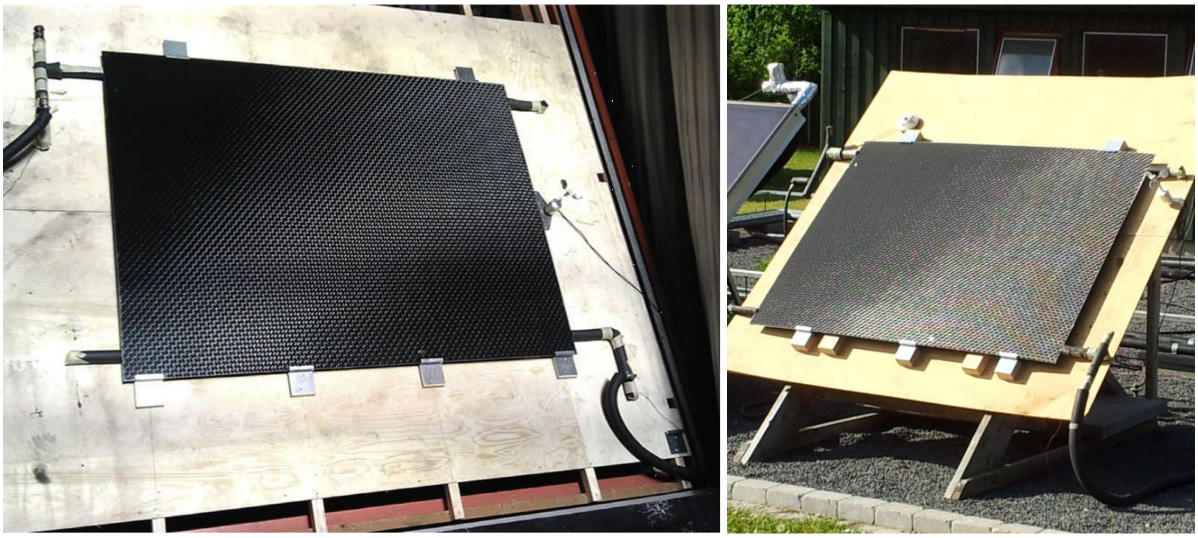


Figure 18 - PVT mockup #2 on indoor and outdoor testing facility

On Figure 18 is seen the second mockup during indoor and outdoor testing. Artificial sun lamp irradiated perpendicularly the mockup mounted on wooden boards with angle of 67,5°. Water flow was supplied across the panel with constant flow and temperature provided by chiller. Air release valve and flow meter was installed. Along the lower edge was installed line of controllable axial fans simulating wind.

There was performed two test sessions, one with low-flow and another higher flow session. Fluid used for pure testing was tap water with two flows 173 and 80 l/h, held constant (0,94 and 0,44 l/min*m2 for mockup #2). Each flow was tested at 4 (inlet) temperature levels, 30°C, 40°C, 50°C and 60°C and wind velocities 0 and 1 m/s. 12 measurement points was recorded per test session when equilibrium was achieved.

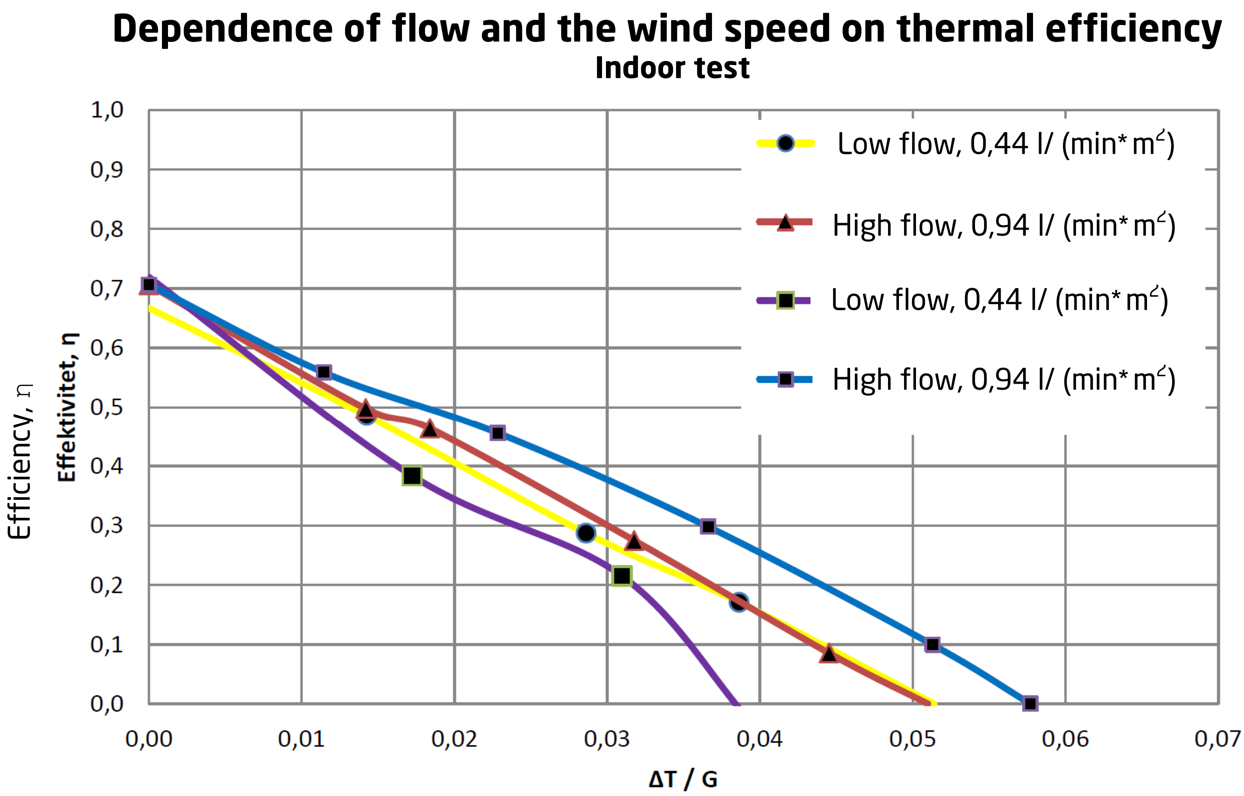


Chart 6 - Mockup 2, Thermal efficiency in relation to wind speed and flow rate (measurement)

The Graph (Mockup Thermal eff.) above presents a correlation between high/low flow rate with and without wind. The thermal efficiency depends directly on temperature difference between mean panel temperature and ambient temperature； indirectly on solar irradiation.

The thermal efficiency started on 66 ~ 72% and dropped to zero when the temperature difference reached 34 ~ 57 K if would be solar radiation 1000W/m^2.

Test results without wind showed very similar outcome, while there is a relatively large deviation between the results at a wind speed of 1 m / s.

Not least, it should be noted that the two sets of measurements with a wind speed of 1 m / s showed unexpected high thermal performance at a high flow rate. In an attempt to uncover the cause was tried several different approaches:

- Smoke tests: Smoke was sent up the panel to see if there was other win or strange currents that influenced the result - Negative result
- Air in the pipes: A high flow rate was sent through the panel to remove possible air bubbles / air pockets in the panel, and the slope of piping was checked to ensure that any air itself would seek to air relive valve - Negative result

It can therefore be stated that the trend is not clear, but may be related to flow type (laminar or turbulent), or simply an expression of measure deviation.

5.2.1.5 *Hydraulic layout of PVT system*

Architectural group gave the layout of the glass roof elements and the task was to decide the hydraulic layout of the system.

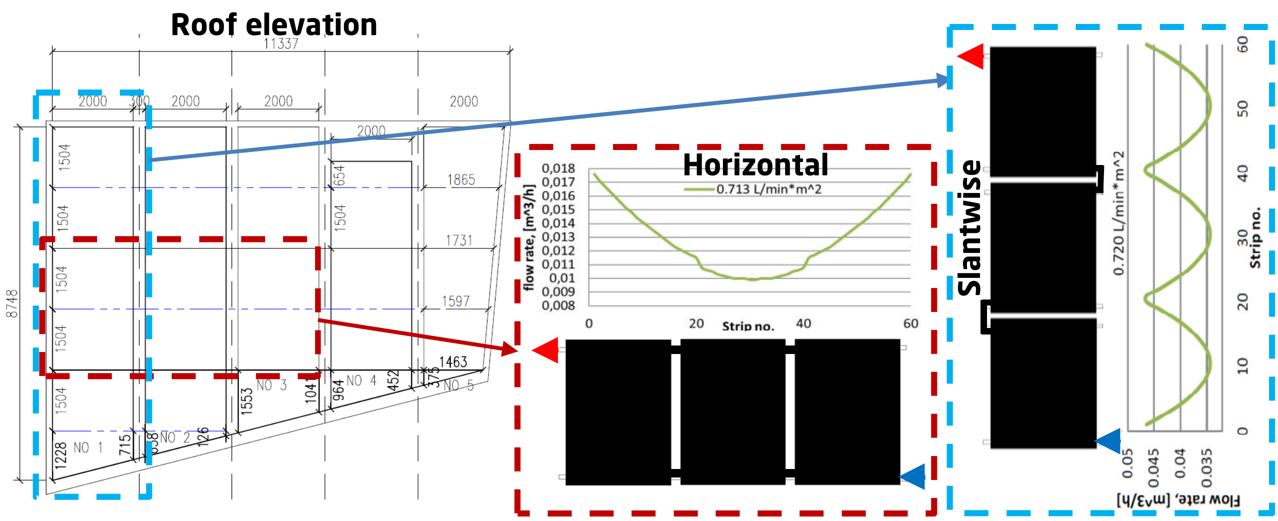


Figure 19 – Hydraulic series layout

For this simulation was considered slightly higher rate. Used was copper piping with manifold/lateral pipe inner diameter of 20/6; spacing 100mm.

The two possible solutions, seen below, were selected (horizontal and slantwise). Investigation of flow distribution through the row and overall system routing was considered.

Horizontal series

- Lower pressure drop
- Less uniform flow rate but the temperature does not rise up significantly across series
- Easier supply/return piping
- Challenging mutual joints between roof elements

Slantwise series

- Higher pressure drop
- Temperature rise up in each panel
- Less demountable joints

Both aforementioned layouts have the pros and cons. The Horizontal series layout was selected due to easier piping, smaller pressure drop and more even temperature distribution. Thus furthermore the roof was hydraulically divided into two arrays, A (3x3 PVT panels) and B (2x2 PVT panels), seen on Figure 20. Argument was lowering the pressure drop on supply/return piping but also the control strategy described in Chapter 6.2.1.8.

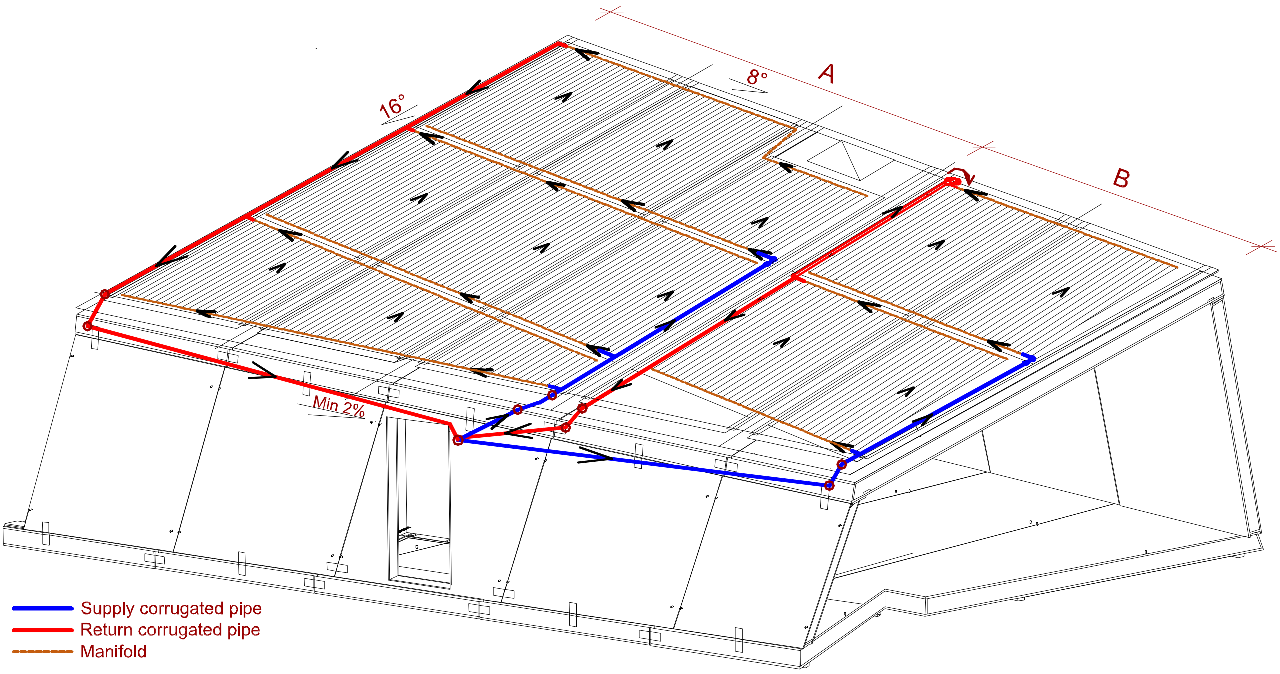


Figure 20 - Axonometry of thermal part of PVT roof system

As is seen on Figure 20 the final division of roof-followed roles about minimal slope of 1% for drain back system.

Array B was divided in 4 similar panels and the array A into 9 more vary shaped panels.

Double wall and gap beneath PVT panels was used for routing supply and return piping. With emphasis was planned the correct slope of pipes in the wall and height of the connection to the drain back tank, seen on Figure 25.

Details of mutual joints between PVT panels, roof penetration and chosen fittings are seen in Chapter 6.2.3.

According the slantwise solution there were assumed 3 panels in a row in the **array A**. Lateral pipes had diameter 8x1mm (6mm inner diameter). Pipe with inner diameter 5mm would suit best but this pipe diameter is rare.

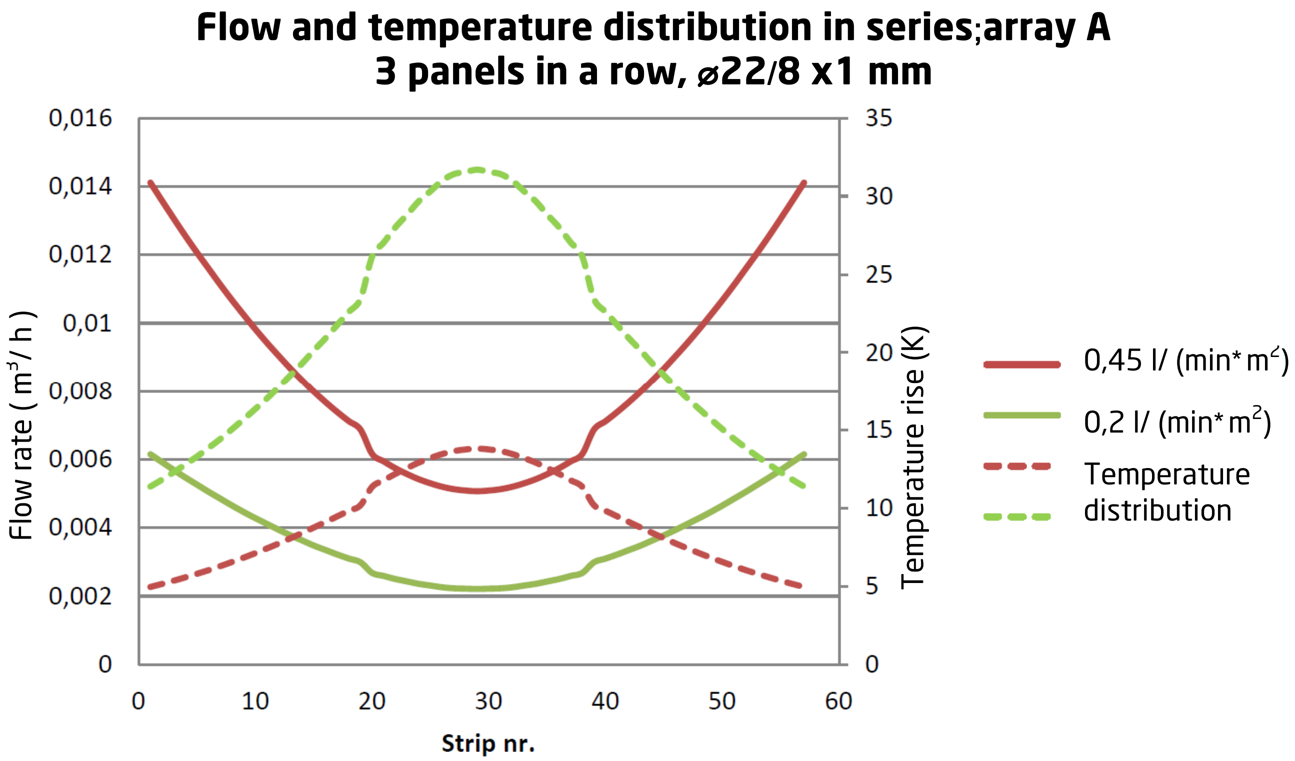


Chart 7 - Flow and temperature distribution in series;array A

Part A was the subsystem that contributed to domestic water heating, and only served cooling when by cold water from bottom of DHW tank. Therefore, expected average temperature in this part of the system was to be higher. Deviation of flow distribution, min / max was 64.1%

The temperature was depending on flow rate in particular place of the collector. The temperature rise in the panels was calculated on the basis of a solar irradiation for thermal part of 850 W/m^2, and a thermal efficiency of 30%, which is expected to be near the maximum that can be achieved for this part of the system as this section will be used to DHW heating in the house.

There were only 2 panels in a raw in **array B**. The best suitable inner diameter 8 mm, pipe ⌀10x1mm for lateral pipes was chosen.

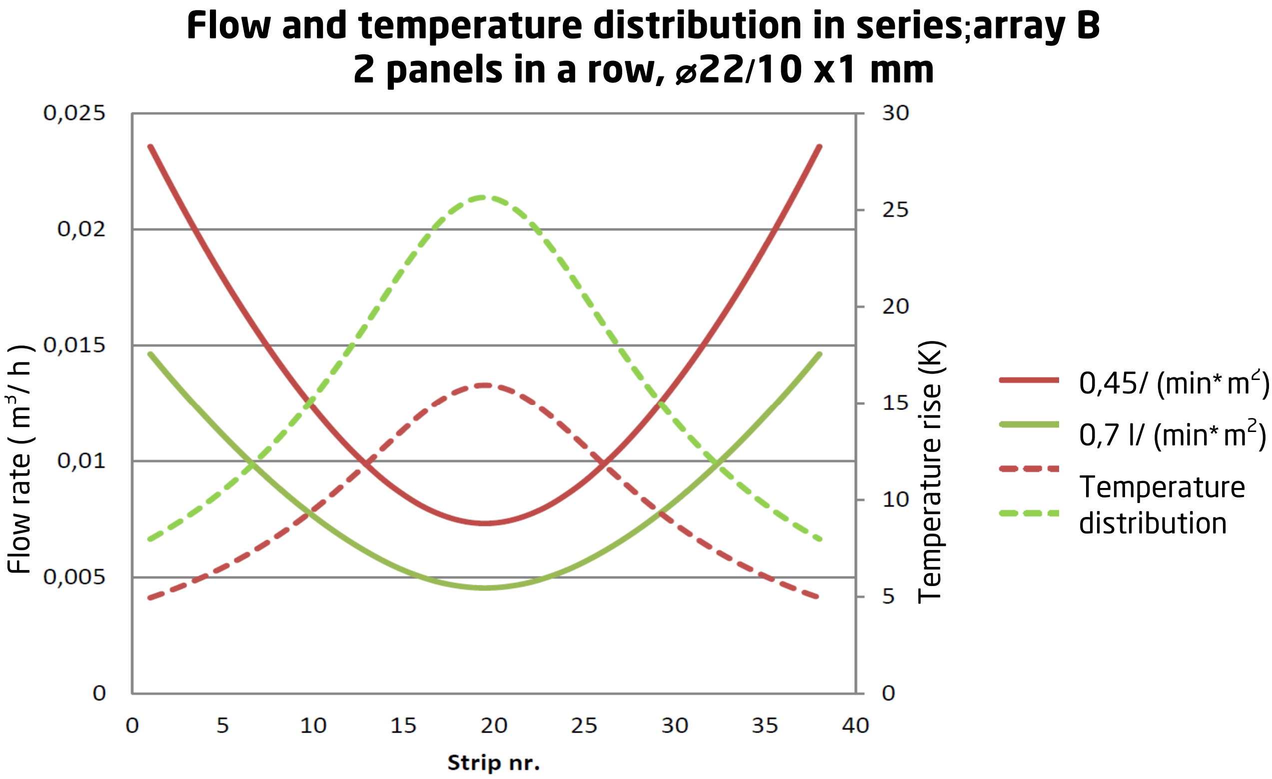


Chart 8 - Flow and temperature distribution in series;array B

This part of the system was used both for cooling of the solar cells and DHW tank heating. The percentage deviation in flow distribution was identical in both volume flows. The temperature rise is again calculated based on a solar radiation of 850 $W/\ m^2$, while the thermal efficiency is set to 50%, since it is expected that the mean temperature of this part of the system can be kept close to the ambient, and thus obtain a high efficiency. Deviation of flow distribution, min / max was 68,9%.

After analysis and calculation of flow distribution in the respective subsystems, the following production dimensions and flow rates were chosen:
(All measurements are outside diameters x thickness)

- Part A:Manifold:⌀22x1 mm;Lateral pipes:⌀8x1 mm;max flow rate =0,45 l /(min x m^2)

- Part B:Manifold:⌀22x1 mm;Lateral pipes:⌀10x1 mm;max flow rate =0,70 l/(min x m^2)

It should be noted that the specified flow rate is a maximum expected value, and that the actual variable controlled flow rate was lower, in most of operating situations.

Lateral pipes for array A and B were found not the same. It was in marginal interest to have as similar flow distribution as possible and that was reached by different sizing. Between flow rate and cell temperature was fond direct dependence, thus for design of electrical division of the PVT arrays (electrical circuits) it what important to follow know the flow distribution in the arrays. A final design simulation showed the flow and temperature distribution for an expected operation conditions. A temperature distribution scheme was created

5.2.1.6 *Real PVT outdoor testing*

The final PVT panel consisted from materials seen below. For the testing was selected panel A 3-2 (according to the roof elevation seen on Figure 22), since this panel had the most similar size of absorber compared to the Mockup #2.

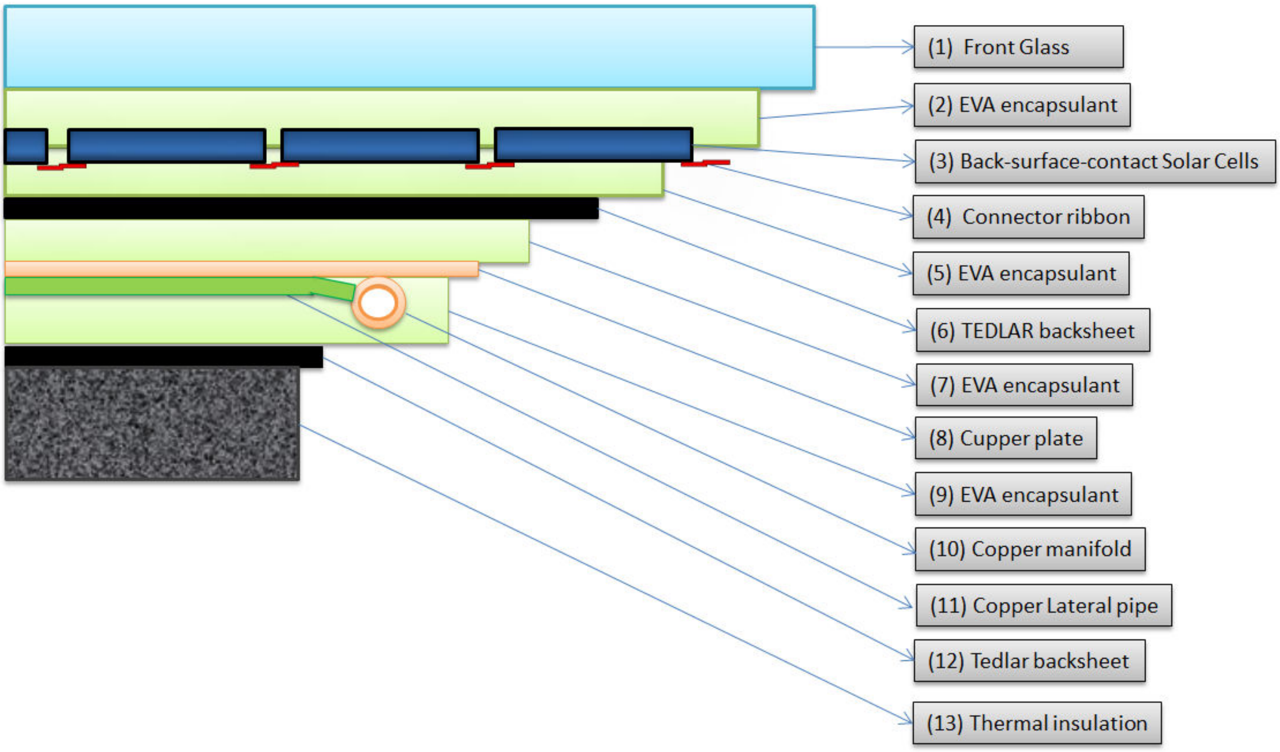


Figure 21 - PVT cross section

Table 2 - PVT material list

Material	Supplier	Product name	Thickness (mm)	Absorption()	Emissivity ()	Transmittance ()	Thermal conductivity (W/m*K)
(1)Glass	Saint Gobain	Albarino G	4,00	0,28*	0,87	0,913	0,98
(2)EVA	STR	Photocap 15420P/UF	0,50	-	-	0,92	0,23
(3)Solar cells	Sunpower	A300 back contact cell	0,20	0,8*	0,2*	-	148
(4) Contact ribbon	Bruker-Spaleck	Cu-ETP1	-	-	-	-	-
(5)EVA	STR	Photocap 15420P/UF	0,50	-	-	0,92	0,23
(6)Tedlar	Isovoltaic	Icosolar 3469 s/s	0,32	0,94	0,9	-	0,36
(7)EVA	STR	Photocap 15420P/UF	0,50	-	-	0,92	0,23
(8) Copper plate	N.N.	N.N.	0,30	0,35	0,04	-	-
(9)EVA	STR	Photocap 15420P/UF	1,00	-	-	0,92	0,23
(10) Copper manifold	N.N.	N.N.	⌀22x1	-	-	-	-
(11) Copper lateral p.	N.N.	N.N.	⌀10x1(array B) or ⌀8x1(array A)	-	-	-	-
(12)Tedlar	Krempel	Akasol PTL 3-38/75	0,18	0,94	0,9	-	0,36
(13) Thermal Insulation	Armacell	Armaflex AF–25mm	25mm	-	-	-	0,035

*Estimated value

PVT manufacturer ensured composition of the PVT panel. Basically was used a typical solution for the PV panel where was extra in-laminated the copper absorber and piping. Team DTU designed and realized the hydraulic system and had a big share on the electrical part design.

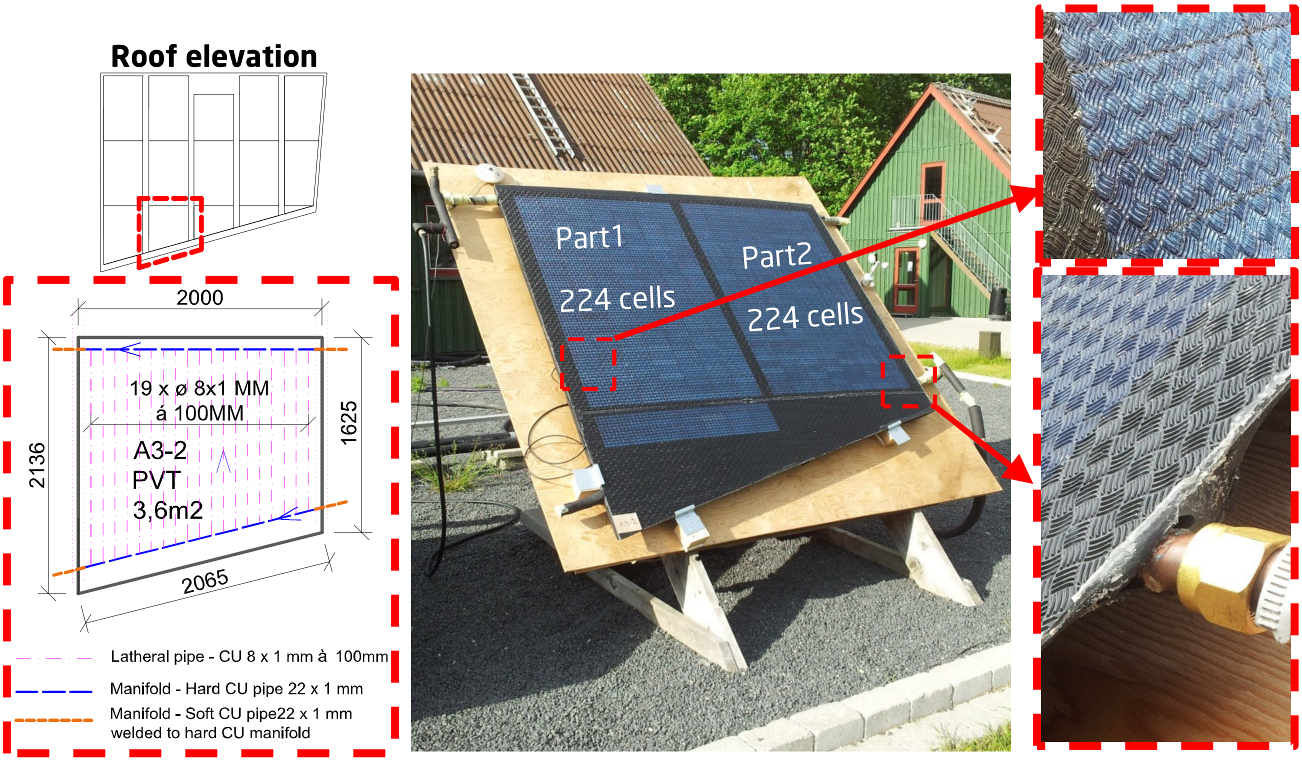


Figure 22 - PVT panel A 3-2 on outdoor testing facility

The panel A3-2 was tested on the same outside testing facility as Mockup #2. The panel was mounted on wooden boards with angle of 67,5°, oriented to the South (same as the indoor test).

Thermal test

The flow rate used for testing,156 l/hour ~ 0,7 l/(min m^2), was supplied through chiller with several different inlet temperature (17 ÷ 56°C). Solar irradiation was measured with pyranometer. inlet/outlet temperature with flow/temperature meters, wind speed with anemometer and finally the panel surface temperature (between Tedlar lamination and Thermal insulation). Data were computerized logged.

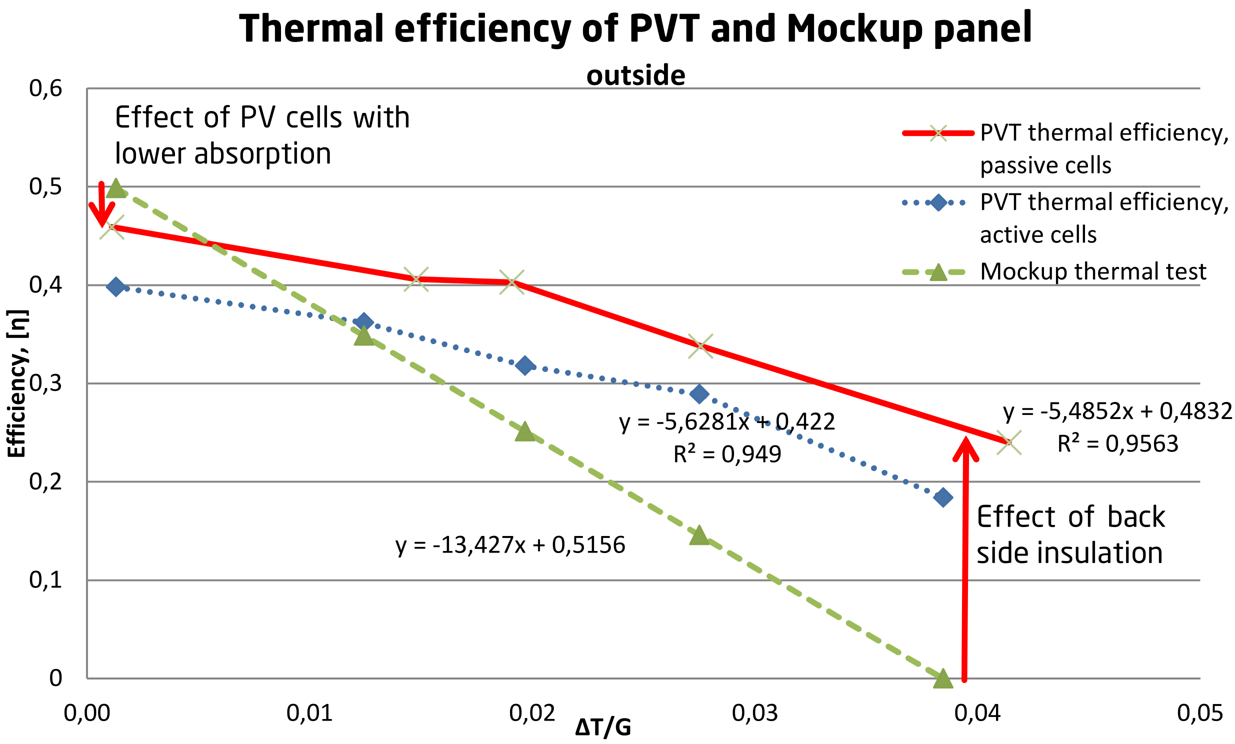


Chart 9 - Thermal efficiency of PVT and Mockup panel

Thermal efficiency of PVT panel with passive cells (like a unglazed solar collector):

$$\eta_{Thermal\ with\ \boldsymbol{passive}\ cells} = 0{,}483 - 5{,}485 \cdot \frac{\Delta T}{G} \ ; \ \eta_{Thermal\ with\ \boldsymbol{active}\ cells} = 0{,}422 - 5{,}628 \cdot \frac{\Delta T}{G}$$

On chart above are seen thermal efficiency curves of Mockup and PVT tested outside in DTU campus during sunny weather with clear sky (solar irradiation 780÷980 W/m^2), slight wind (below 1m/s measured on setup) and air temperature 19÷23°C.

The result of the thermal testing of PVT panel showed a surprisingly low heat loss coefficient as compared to the tests on mock-up panel. The effect of insulation placed on backside flattens the efficiency curve (seen on Chart 9) and by other words increased range of working conditions.

Even the number of lateral pipes in the panel was increased from 12 to 19 the starting efficiency dropped (seen on Chart 9). The reason was to be found in the solar cells that changed the panel´s the optical properties, mostly the absorption coefficient. It was not possible to ascertain the exact values of the used solar cells optical properties, but is typically photovoltaic absorptivity of 0.6 - 0.8, which is significantly lower than tedlars, which is the governing mock-up panel absorption.

Electrical test

The electrical testing was performed on the same testing setup as Thermal test. Voltage and current were measured manually using the "Uganda" method". This simple method was not the most optimal, but since the delivery of the agreed test equipment did not materialize, this test setup, with great help from the Department of Electrical engineering, was established as a sufficient solution.

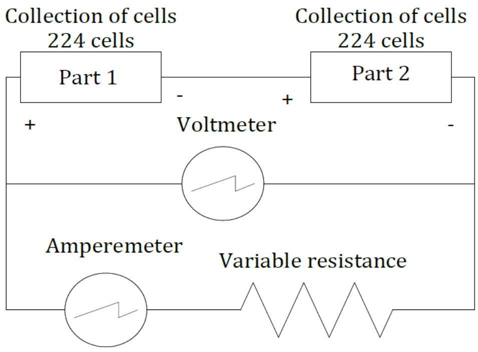


Figure 23 - Electrical scheme of testing setup

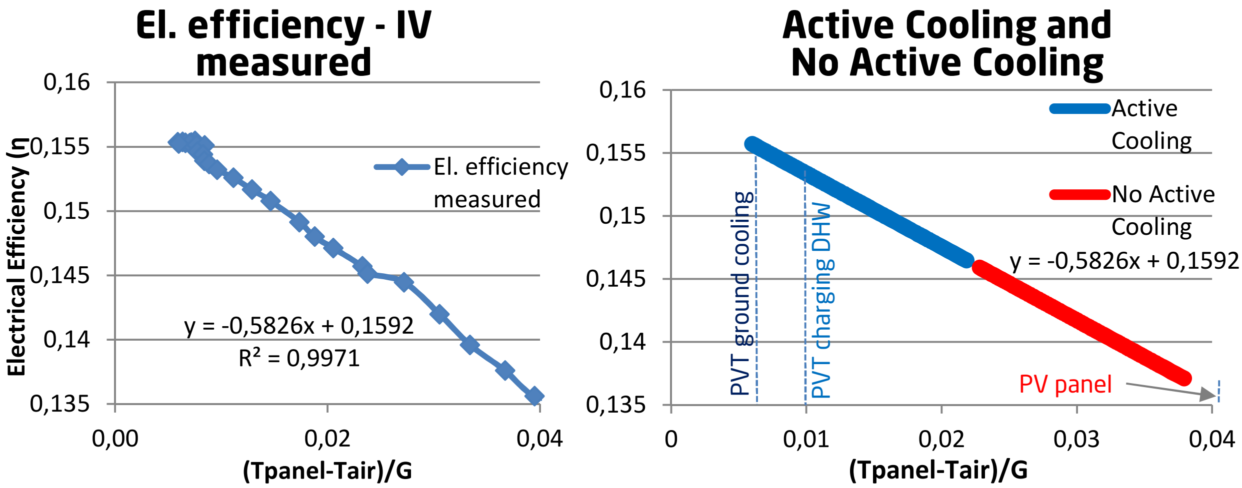


Chart 10 - El. efficiency of PVT panel A3-2

The results of the electrical tests (left Chart 10) must be considered disappointing as the results for standard testing conditions was about 24% lower (15,9% instead of 20,8%) than expected based on the data sheet for solar cells A-300. The lack of performance may be attributed only by a small part to the accuracy of the measurement because the result was too far from expected value. Perhaps more advanced equipment with "maximum power tracker" would give clearer answer.

The electrical test of the Active Cooled/Non Active Cooled panel (right Chart 10) was done during a normal temperature level under moderate Danish summer weather conditions. The three marked efficiency levels corresponds to STC with vary panel temperature on three typical levels: 32°C for PVT ground cooling; 35°C for PVT charging DHW tank and 66°C for normal PV panel.

The electrical properties of PV cells itself stayed unchanged regardless of the cooling mode but the active cooling provided lower cell temperature and the higher el. efficiency followed, even same boundary condition .

$$\eta_{PV\ cells} = 0{,}159 - 0{,}583 \cdot \frac{\Delta T}{G}$$

Firstly was performed the IV measurement of electrical efficiency of the PV cells. The efficiency curve for Active / No Active Cooling was idealized by using (trendline) equation obtained from IV (current – voltage relation) measurement with real measured temperature conditions as an input.

The impact of cooling depends on the percentage of maximal performance, thus the cooling effect was also limited by the lack of efficiency. The maximum measured efficiency growth achieved during testing was 2% (13,5 ÷ 15,5%) seen on Table 3. However, it was expected just an increase of 3%, according to the measured temperatures with and respectively without cooling. This lost part of the rise of efficiency would create a significant offset of increased investment and increased operating costs of about 1/3 in compare the cells would operate as expected. This observation negatively influenced the energy merits and economical point of view of cooling the solar cells. See economy Chapter 6.4.

Table 3 - Active Cooling impact

	Efficiency (%)	Panel temperature (°C)	Air temperature (°C)	Solar irradiation (W/m^2)
Active cooling	~15,5	32±0,5	22,5±0,5	880÷950
No Active cooling	~13,5	66±0,5	22,5±0,5	880÷950

Was not possible for author to clarify and investigate reasons for the low efficiency of such a product as the PV panel was. To the examination could not interfere anyone other than the manufacturer. It would boldly speculate erroneously manufacturing process or product malfunction even if Part 1 of the test panel gets damaged during testing. The above-mentioned results were obtained from Part 2, which showed normal results throughout entire testing.

Electrical and Thermal simultaneous test

This unusual test was de facto done computably by examination the data obtained during previous testings.

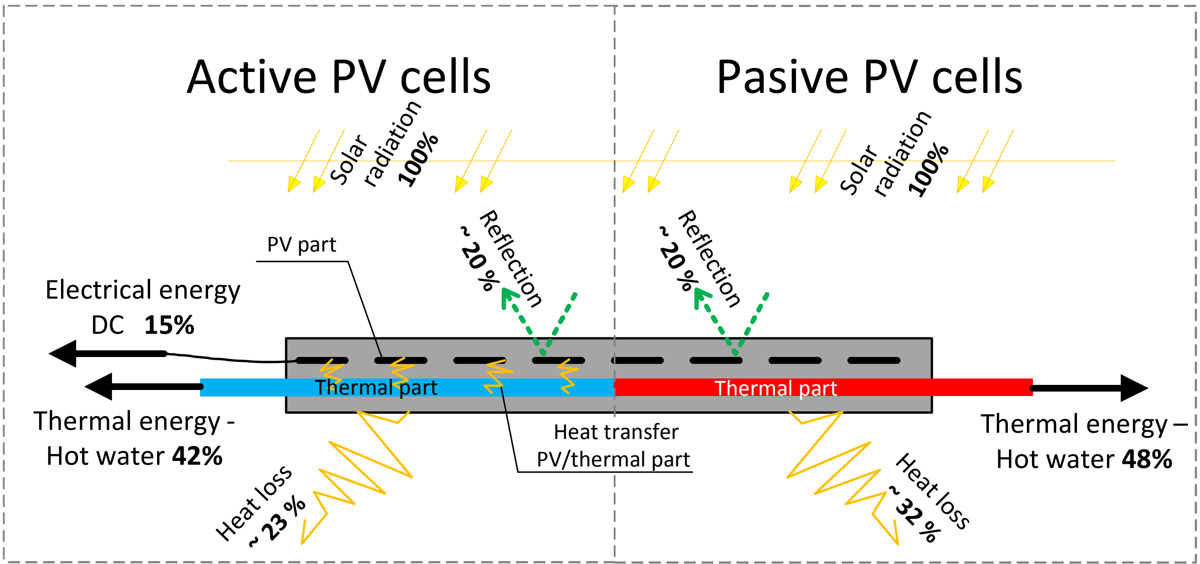


Figure 24 - PVT panel - energy balance

Thermal efficiency was measured under two circumstances: with PV cells **active** and **passive**. The efficiency measured with active cells was about 12,5% relatively lower (8% absolutely) due to transformation of solar irradiation to electricity (about 15% absolutely). Since the PV cells were placed in layer above the thermal part the active cells "stolen" particular share of energy that was transported from panel as a direct current. Thus thermal part, placed below the cells, obtained less energy to produce heat. The deficit of thermal efficiency (8%) is not equal to the efficiency of PV part (15%) because the cells, when active, also significantly heat up by itself, what slightly improved the heat obtained to absorber. The overall energy balance stayed equal as seen of Figure 24 that presents estimated energy balance for each PVT working mode.

$$\eta_{El.\ 50°C} = \eta_{El.\ 25°C} + \eta_{El.\ 25°C} \cdot \frac{K_{tab}}{100} \cdot (25 - 50) \rightarrow K_{tab} = 0{,}366\%/K$$

The **power temperature coefficient** (The relative change in panel output power for temperatures other than 25°C given for 1K difference) was found to be 0,366 %/K. This value was again lower than expected according to the data sheet (0,38%/K), see Appendix C.

In it must be noted that the panel temperature of cooling is not uniform over the whole panel but is rising in the direction to roof ridge. Therefore, it is also expected that the highest panel temperature is approx. 5 K higher than the measured since the measurement was done in the middle of the panel. During the test was recorded rise in temperature of the water of approx. 10 K.

The testing outputs were used from the publication *Borgesen J., Nielsen K.(2012). Author* regularly collaborated with authors on observed material.

5.2.1.7 *Circulation pump flow rate*

An optimal flow rate of the solar thermal system and optimal temperature rise through the PVT were issue to optimize. In this purpose a simple static calculation were performed where for STC was performed. Calculation was done for 3 inlet temperatures Ti: 25, 30 and 35°C. Then 4 different temperatures rises Tout-Tin: 5, 10, 15 and 20K. The appropriate flow rate was imputed. The desired output was a **comparison of the electricity usage** for circulation pump and for Heat pump to charge the DHW tank from 15 to 60°C same as find out ratability of the water cooling. Additional information was the actual **energy balance of PVT** arrays for specified conditions and the **extra contribution from the electricity production** for each case caused by circulating the water. Due to the electrical transformation losses, the output was decreased to 93% and the thermal power was reduced to 80% because of the heat losses.

Table 4- Scenarios for various temperature and flow

	Unit	Variable	Scenarios for various temperature rise; irradiation 1000W/m² and air temp. 25°C												
1	K	Tout - Tin	**5**	**10**	**15**	**20**	**5**	**10**	**15**	**20**	**25**	**10**	**15**	**20**	**25**
2	°C	Tin	25	25	25	25	30	30	30	30	30	35	35	35	35
3	°C	Tout	30	35	40	45	35	40	45	50	55	45	50	55	60
4	°C	Tp	27,5	30	32,5	35	32,5	35	37,5	40	42,5	40	42,5	45	47,5
5	m³/h	Flow rate	1,471	1,062	0,98	0,654	1,362	0,98	0,752	0,599	0,49	0,899	0,686	0,545	0,443
6	W	Pump power	140	81	76	76	140	79	76	76	76	76	76	76	76
7	%	Electrical eff.	**15,92**	**15,63**	**15,48**	**15,34**	**15,48**	**15,34**	**15,19**	**15,05**	**14,9**	**15,05**	**14,9**	**14,75**	**14,9**
8	W	Electrical output	10032	9850	9755	9667	9755	9667	9572	9484	9390	9484	9390	9295	9390
9	%	Therm eff	39,4	36,6	35,2	33,8	35,2	33,8	32,4	30,9	29,5	30,9	29,5	28,1	26,7
10	W	Therm P. No th. losses	21358	19840	19081	18322	19081	18322	17563	16750	15991	16750	15991	15232	14474
11	W	Therm. P with th. losses	20404	17932	16219	14506	16219	14506	12793	11026	9313	11026	9313	7600	5887
12	%	Heat losses perc.	4%	10%	15%	21%	15%	21%	27%	34%	42%	34%	42%	50%	59%
13	Wh	El. energy load for runing the circulation pump Pumps 3,5 to fully charge the DHW tank to 60°C	64,6	42,6	44,1	49,4	81,3	51,3	56,0	64,9	76,9	64,9	76,9	94,2	121,6
14	Wh	El energy for Heat pump to charge the 180l DHW to 60°C (COP 3,28 to heat up)	2872												
15	L/ min*m²		0,54	0,39	0,36	0,24	0,50	0,36	0,28	0,22	0,18	0,33	0,25	0,20	0,16
16	W	Electrical balance (PV output + Thermal output/COP - circulation pump cunsumption)	16113	15236	14624	14013	14560	14010	13397	12770	12153	12770	12153	11536	11108
17	Wh	Extra generated electrical en. decreased by load for runing circulation pumps to fully charge the DHW	549	590	603	617	635	732	765	812	866	968	1051	1171	1663
18	W/m²	Extra el. effect of w. circul.	19,6	17,78	16,46	15,15	18,21	17,81	16,46	15,15	13,76	17,85	16,46	15,06	16,46
19	W/ arrays	Extra el. effect of water circulation in arrays	1328	1205	1115	1027	1234	1207	1115	1027	932,3	1210	1115	1020	1115
20	%	Adequate PV efficiency	13,59	13,59	13,59	13,59	13,3	13,3	13,3	13,3	13,3	13,01	13,01	13,01	13,01

The results from the calculations showed that for appropriate conditions is more beneficial to produce the hot water by the water circulation before the use the Heat pump. Moreover, the electricity generation is improved in the same time. The actual energy balance including the generated electricity and heat decreased by pump consumption is shown in line 16 of the Table 4. The energy balance is mostly influenced by the thermal output.
The electricity generation is directly dependent on the panel temperature as is seen in line 4 and 7. A strong argument in discussion if the cooling is beneficial is the ratio between extra consumption

of energy used by pumps to generate extra energy. In line 18 and 19 are seen the extra net electrical energy generated by water cooled PV cells.
As a paradox might seem the result of line 17 where the extra el. energy generated during charging DHW tank is in completely reverse order to Energy balance seen in line 16. The value in line 17 is most positive with the highest el. efficiency. Lower thermal efficiency that makes tank charging longer and therefore the cooling and generation of panel clarify this fact last longer. Simply stated this result should be taken into account only if the active cooling in the ground is not possible and the only active cooling of PVT would be done through DHW tank.
Main output of previous research is the design flow rate. Scenarios found as optimal for the DHW tank-heating mode are marked re in first line of table （Table 4). It is scenarios with temperature difference of 5 or 10K, thus the heat loss is not significant but the extra electrical effect is still high and the electrical load of circulation pumps is marginal. The maximal design flow rate for DHW tank heating mode was stated as 0,45 l/min* m^2.

For the cooling mode, when water circulates between ground and PVT, the highest feasible flow rate due to pressure drop is selected as 0,7 l/min* m^2.

(Iteration process when the system and panel pressure drop was calculated and changer obtained the maximal feasible flow rated repeatedly).

5.2.1.8 *PVT control logic*

PVT panels cover almost entire roof, around 67,76m^2 of an active area that includes electrical cells and piping system. The "thermal" system is divided into 2 arrays, higher circuit A with area 45,35m^2 and lower circuit B, 22,41m^2. More symmetrical distribution of the arrays prevents the position of roof window.
The main idea was firstly charge the DHW tank with "free" heat removed from PVT´s by water circulation. When no more heat to DHW tank is needed, the cooling takes place via a bore hole, so that PVT´s there ought to be able to obtain very low temperatures and hence improve the electrical performance even more.

Function of **circuit A** was determinate to supply heat to DHW. The circulation Pump 5 operated when the average temperature of PV/T panels T7-A was by 6 K higher than the temperature at bottom of the DHW tank T12. Circulation continued running as long as the return temperature "T5-A" (to PVT´s) was bigger than temperature "T-6AB" measured just before the DHW tank (circulation inlet) and when the upper temperature in DHW tank did not pass 90°C. Circulation pump 5 (circuit A) provided maximal flow rate 0,45 l/(m^2 x min) = 1,224 m^3/h. The pressure drop was then 25,9 kPa or 24,0 kPa if also the Pump 3 (circuit B) worked simultaneously.

"Control A"
1. T12 < (T7-A - 6K)
2. Run P5(at design flow rate), as long as T5-A < T6-A/B & T11<90 ° C
3. V5=0 degrees (because PV/T area B is also joining)

Circuit B has 2 function futures:

PVT charging DHW tank: First priority is to charge the DHW tank. If the circuit A is already running check if also average PTV panel temperature T7-B is higher by at least 6K than temperature at the bottom of the DHW tank T12. Then open valve V10 to 0° and valve 5 to 90°. Then run Pump 3 at design flow 0,45l/(m^2 x min) = 0,605 m^3/h what corresponds to pressure drop of 9,1 kPa when Pump 3 (Circuit B) works simultaneously with Pump 5 (Circuit A).

1. V10 = 0 degrees (open) and V5=0 degrees
2. When conditions in Control A are met, check T7-B, if also T12 < (T7-B - 6°C) , if this is satisfied then run P3 (at design flow rate)

PVT cooling in ground: If no DHW tank heating was desired (the previous conditions failed) and if no house cooling was running (the temperature in embedded pipes T13 is higher than 18°C) check if the solar irradiation is measuring daylight and if the PVT panel temperature T7-B is higher than 35 °C . Then close valve "V10=90°" and "V5=90°" run Pump 3 at 0,7 l/(m^2 x min) = 0,941 m^3/h with total pressure drop 18,5 kPa.

1. V10 = 90 (closed), V5=90, V1 and V2 keep their positions in cooling mode
2. If radiation is higher than 900 W/m^2 or T7-B >35°C and if there is no house cooling (obtained fro m T13) and if there is no DHW need(obtained from Control A), run P3 for PVT cooling with the design flow rate
3. Stop when any of these conditions are not fulfilled any more and check for control 3

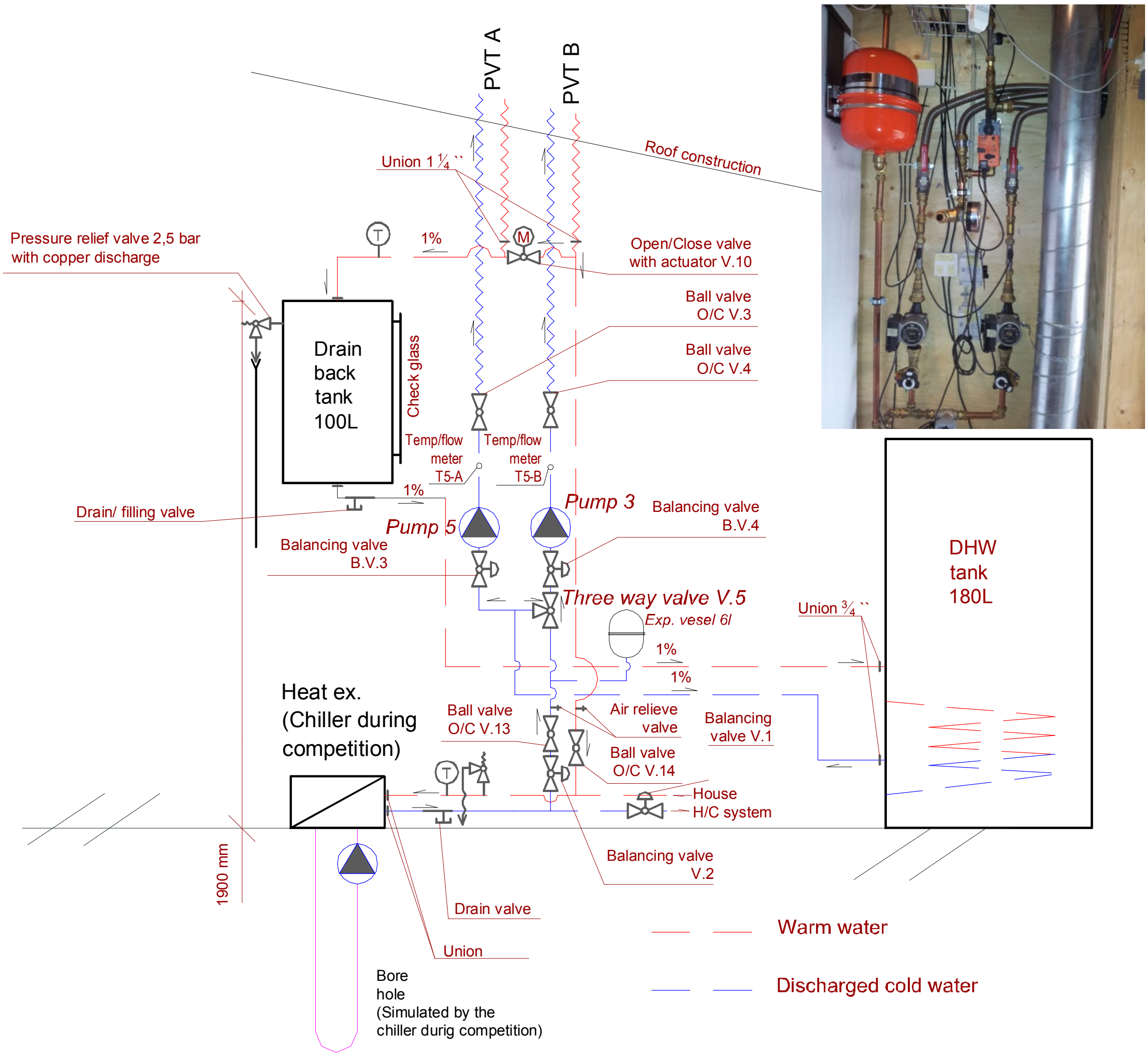


Figure 25 - Scheme of thermal part of PVT system

Pressure drop calculation

The calculation of pressure drop for piping embedded in the PVT panels was already investigated in the hydraulic series layout. In order to select correct circulation pumps the pump head and overall pressure drop of the system was desired. The thermal circuit was designed for various working modes in the sense for various flow rates.

Table 5- Hydraulic characteristic of the system operation

Pressure drops of circuits A and B for different scenarios	Flow rate (l/min/m^2)	Flow rate (m^3/h)	Friction pressure losses (kPa)	Local pressure losses (kPa)	Total pressure losses (kPa)	Pressure losses pump head H (m)	Lifting height (m)	Total pump head (m)
Pump A - Circuit A *is used for heating DHW, circuit B works separately for cooling PVT*	*0,45*	*1,224*	*18,5*	*8,3*	*26,8*	***2,8***	4	**6,8**
Pump B - Circuit B *is used for cooling PVT , circuit A works separately for heating DHW*	*0,7*	*0,941*	*6,3*	*12,2*	*18,5*	***1,9***	3,3	**5,2**
Pump A - Circuit A *and B are used simultaneously for heating DHW*	*0,45*	*1,224*	*18,4*	*6,2*	*24,6*	***2,6***	4	**6,6**
Pump B - Circuit B *and A are used simultaneously for heating DHW*	*0,45*	*0,605*	*4,3*	*4,7*	*9,0*	***0,9***	3,3	**4,2**

As a most appropriate a pair of pumps UPM2 25-75, 180mm long was chosen. Pump producer representatives approved design.

The detailed "handmade" pressure drop calculation for each of four scenarios and pump diagraph are seen in Appendix H.

Calculation of volume of Expansion vessel and Drain back tank is seen in Appendix I.

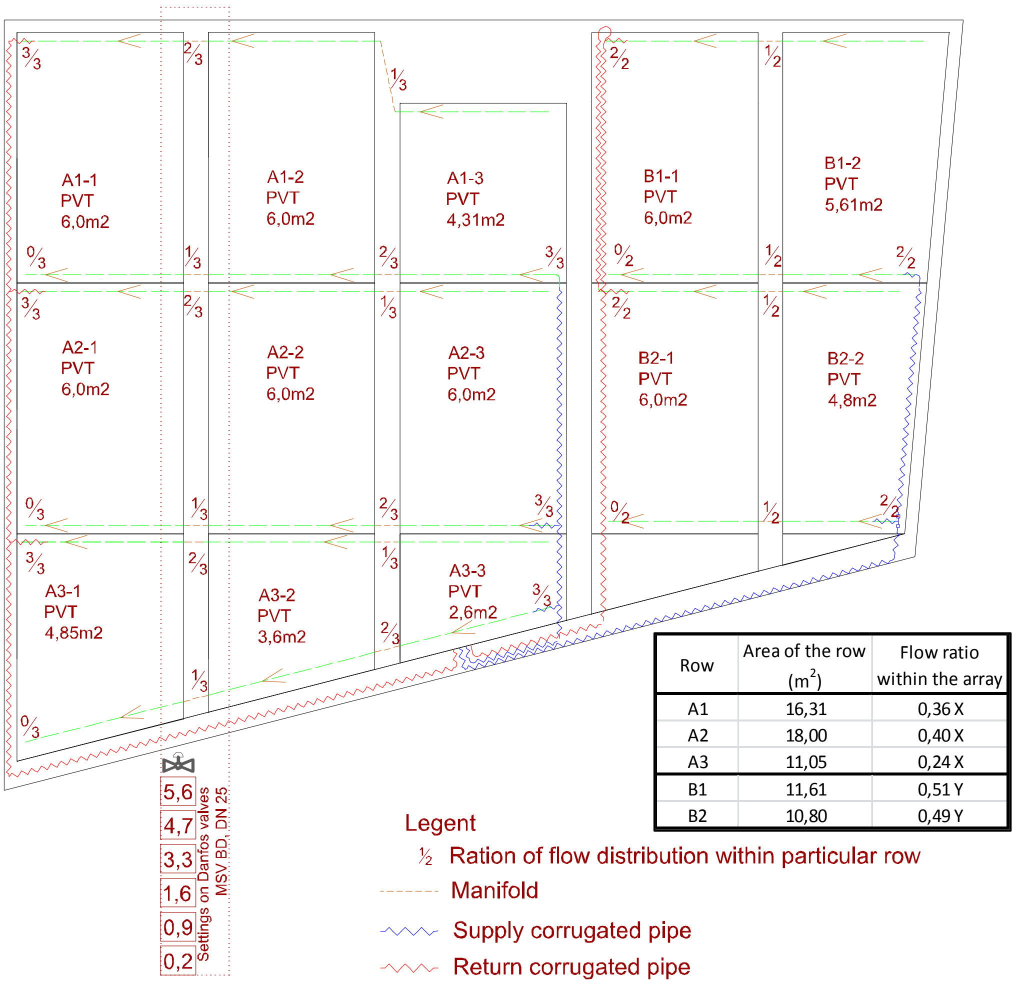


Figure 26 – Flow ratio within the array

To keep as same flow rate per meter squared across the array as possible the flow ration for each node of arrays A and B was stated, seen on Figure 26.

Array B had 4 panels with similar proportions thus a Tichelmann connection was used to simplify the balancing between first and second row on return or supply. The array B was free of valves, balancing was driven by same pressure drop for both rows.

Array A with division 3x3 panels was proportionally less uniform thus 6 balancing valves; 1 for each manifold; were considered to place in the joint between first and second panels, counted from the highest point.

The balancing was done in situ when the FOLD house was built in Madrid. More in Chapter 6.2.3.

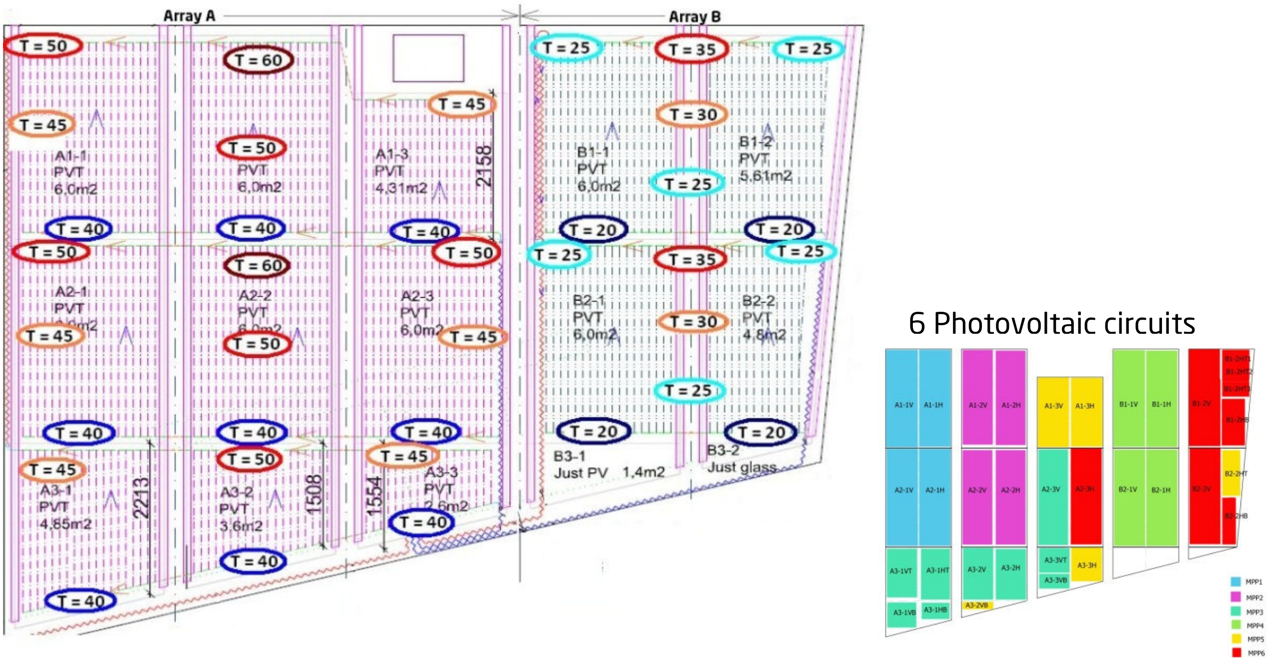


Figure 27 - Temperature distribution in arrays A and B

The Figure 27 is showed an expected temperature distribution under the following conditions:

"Array A: Inlet temp of 40°C (outlet: 54°C), mean thermal efficiency coefficient of 0.5 and with the design flow rate, 0.45 L/min*m^2 (Hot water production mode)

Array B: Inlet temp of 20°C (outlet: 32°C), mean thermal efficiency coefficient of 0.7 and with the design flow rate, 0.7 L/min*m^2 (Cooling mode – flow from PVT was directed to the bore hole)." *Borgesen, J., Nielsen, K.,* 2012

The absolute temperature values were not the primary objective of this simulation but the mutual ration of temperature over the thermal arrays. This has been found as a key aspect for design of the electrical strings for PV`s. Each electrical circuit followed zones with most similar temperatures. The PV design seen of Figure 30.

5.2.2 PVT - Photovoltaic part description

PVT team did the PV and electrical design during development process of the FOLD.

For the PV part was used monocrystalline cells embedded and conducted with EVA film, to protect the module from weather, to textured glass. The textured glass reduce glare and thus absorb more light. When the reflected light incident the glass/air boundary second time, part of sunbeams are trapped and mirrored back. The textured glass supposed to give 3 % extra efficiency under IEC 61215. The textured surface makes the PV modules look more solid and extraordinary in compare to conventional PV panels. Figure 28 （*Team DTU*, 2012）

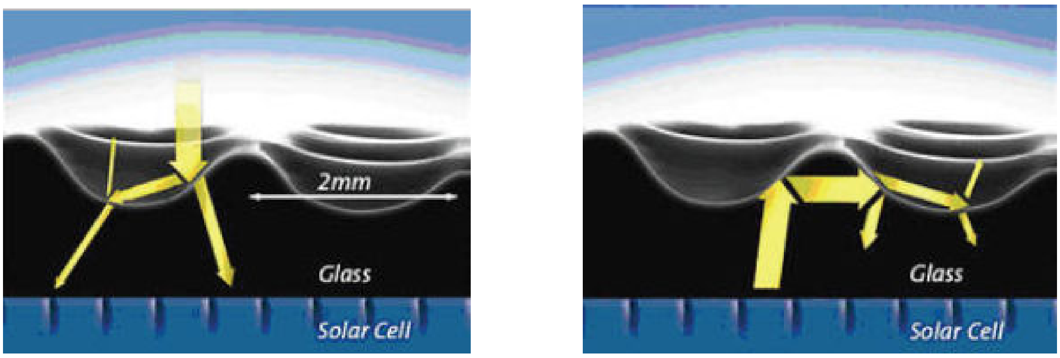


Figure 28 - Textured glass with trapping effect

Figure 29 - PVT modules mounted on FOLD house

In FOLD house were rectangular used „mono crystalline silicone" cells that were cut in to 3 pieces, each of 41x125mm. In total was used 9914 cells with total cell area of 50,81 m^2. The bypass diodes were integrated inside the lamination (4 cells per diode). Thus, in case of failure only certain number of cells is out of order and the panel still produces power. No junction boxes were used for the PVT modules, only fixture for cable outlets.

The panels were interconnected in 6 separate strings without direct dependence on the specific panel since across the panel's were not even thermal conditions. (seen of Figure 27） Most of the strings were made up of 448 full cells (3 cut cells) with maximal power voltage of 298V (0,66V per cell) and short circuit current 8A. Total installed nominal power was 10,8 kWp that was electronically cut down by inverters to 9,2kWp.（see the Appendix D） The panels are mutually connected in parallel to meet the Danfoss inverter requirements about range of each string (MPP) between 180÷350V, max 450V and 10A current per each of 3 string.

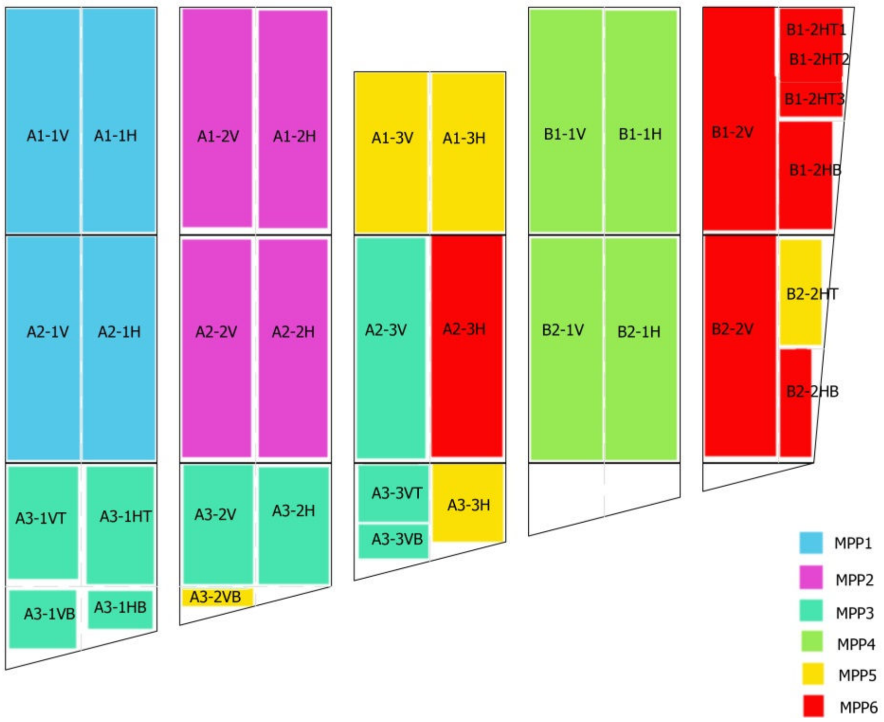


Figure 30 – Photovoltaic circuits of the PVT arrays

Figure 30,*(Team DTU)* presents the photovoltaic string division on the roof. Location of the MPP´s was based on the thermal zones given by the solar thermal part. Photovoltaic electrical chart is documented in Appendix U.

The two pieces of Inverter that met the organization requirements were used for the FOLD; ULX5400i MV. The nominal AC power for the inverter was 4600 W. The maximum AC output power of 5000 or 5400 W regarding regulations in given country. For Madrid the AC maximum power output 5000 W whereas in Denmark 5400 W. FOLD was connected according to the Net metering concept when the energy is firstly used on site and only surplus or deficiency is traded with the grid

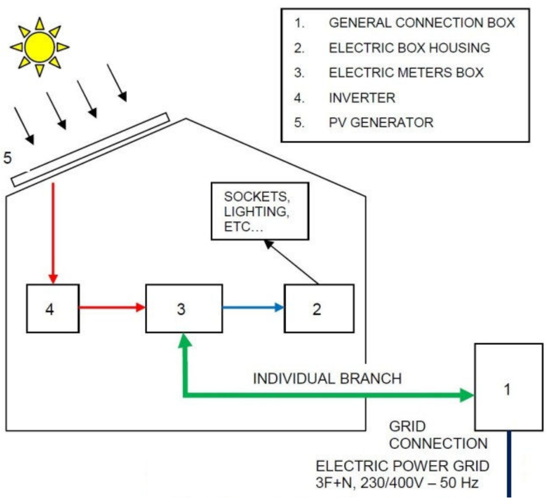


Figure 31 - Net metering scheme

The PV cells were grounded via inverters and the thermal part by the metal piping inside the technical room with a 2.5 mm^2 copper wiring (See drawing PV-031). To see wiring after the inverter see drawing PV-011 and PV-021. Whereas of the PVT panels were mounted on wooden battens, no direct grounding was required.

Characteristic for the PVT module and further information regarding the PVT modules compliance with IEC standards can be seen in Appendix C.

Electricity storage

The electrical energy storage became an issue of ethic. It was believed that there is no reason to have electrical energy storage in house that is grid connected. The transformation of electricity between DC/AC several times before is used cause significant losses and moreover there is environmental burden of the batteries.

An elegant solution was proposed by Professor Bjarne W. Olesen to use car as a temporary battery for the competition period. The battery would have a positive effect on energy correlation and after the competition just drive away.

Looking at today' s market the car battery could be used as an application of Smart city concept when the renewable & classical sources of energy and energy storage are shared and works both ways within a specific territory.

For completeness was done the following investigation about the battery usage and its effect on annual energy balance and economy for FOLD house located in Spain. Lead Calcium battery bank with capacity of 257 Ah (3,084 kWh) / 12V and dimensions 527/279/270mm was used.

Table 6 - Electricity storage balance and economy for Spain

Capacity of battery bank Ah (kWh)	Investition to the battery bank with lifetime of 8 years (€)	Annual electricity extracted from grid (kWh)	Annual reduction of extracted electricity with battery b. (kWh)	Price of elecricity (€ per kWh)	Annual reduced costs for the purchase of el. energy (€)	Payback time (years)	Total cost payed for electricity within 8 years (€)
No batteries	0	5987	-	**0,178**	-	-	**8511**
257Ah (3,084 kWh)	473	3408	**2579**	**0,196**	506	0,9	**5825**
514Ah (6,168kWh)	946	2485	**3502**	**0,201**	702	1,3	**4932**
771Ah (9,252kWh)	1419	2061	**3926**	**0,202**	795	1,8	**4757**
1028Ah (12,336kWh)	1892	1798	**4189**	**0,204**	853	2,2	**4821**

Price in Euro per kWh of Electricity for annual consumption is linearly scaled between known tariffs; Spain in May 2012

In 5 annual hourly based simulations was compared effect of "no battery" up to "4 same battery banks" connected via main terminal blocks to the PVT ´s and electrical circuits in the house. For all scenarios the same weather conditions and the same energy usage was considered. The energy surplus was stored in battery banks and subsequently discharger during nonproductive periods what improved the energy balance.

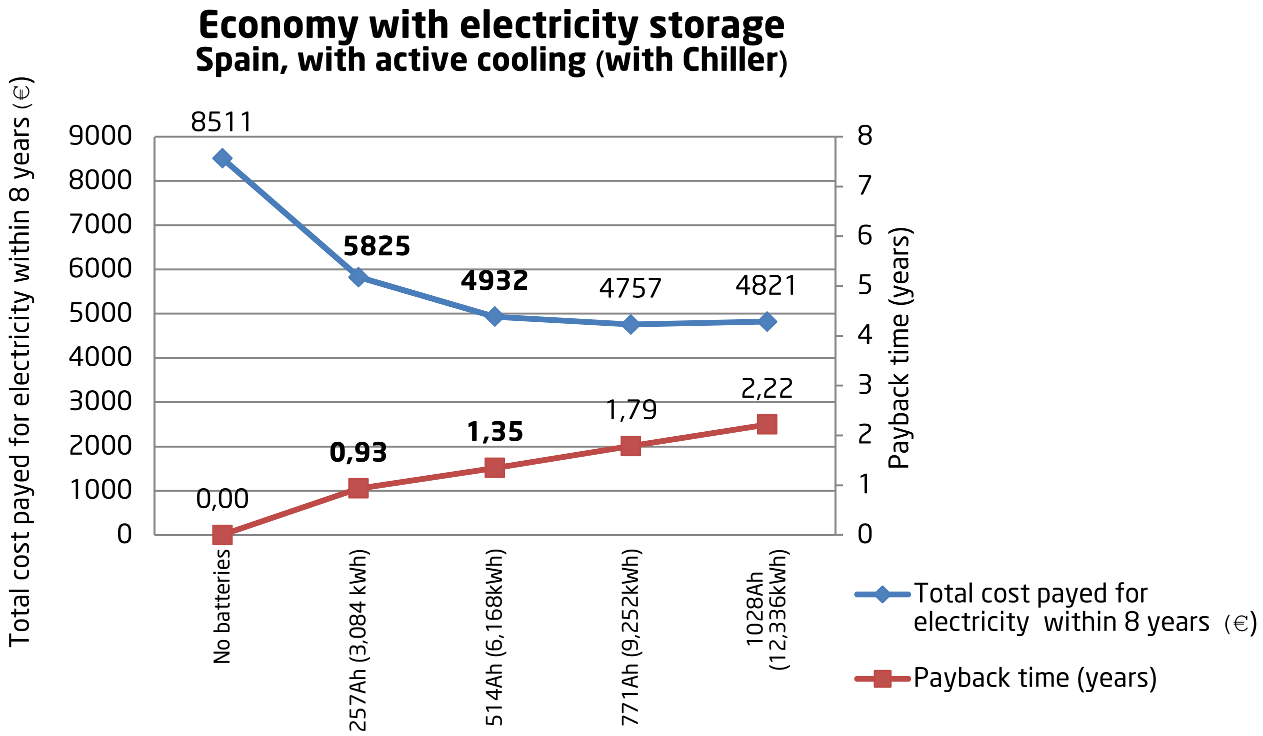


Chart 11- Electricity storage economy

The "Total cost paid for electricity within 8 years" included the payment for reduced electricity usage within the battery lifetime and the investment in the battery.

Slope of both curves seen in Chart (Electricity storage economy) determined the appropriate scenario as the one using 2 batteries (514 Ah) or possible second scenario with one battery (257Ah).

These two scenarios were recognized because of relatively fast down drop of blue curve "Total cost for electricity" even with very short payback time. The two last scenarios had very low inclination and the payback time rose.

The stated conclusion is based on hypothesis that the used only pay for electricity and no surpluses are sold or that are sold with very bad rate.

The technical specifications of battery are seen in Appendix E.

5.2.3 Construction solution of PVT system

The house is intended to be several times assembled and disassembled thus mutual connection of the elements should be dismountable to. The realization process of PVT production done on DTU is described in Appendix J.

Joint between neighbor panels

Manifold was made of hard copper pipe ⌀22x1mm. Both ends were soldered with soft copper pipe of the same diameter as the hard copper pipe. This solution made the connection more flexible and allowed slight adjustments even after the panel was done.
The soft copper pipe was connected with fitting SO-SDN25-CU22 with clamping ring; insert with protection ring against the press the soft copper pipe was used. To the other side of fitting was fastened the flexible stainless corrugated pipe with UV protected insulation. In addition, here the clumping ring was used. The clamping ring permanently bites in the pipe. The middle part of fitting was dismountable by male/female threads with gasket.

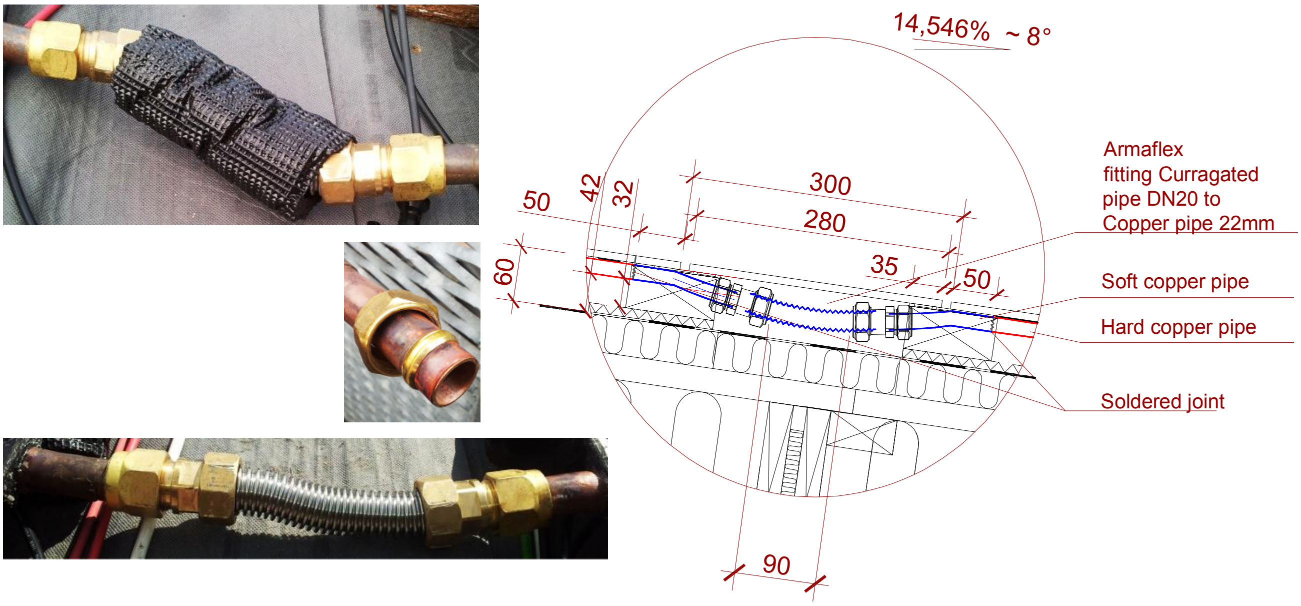


Figure 32 - Connection between neighbor panels, Detail SW1

5.2.3.1 *T-piece joint*

Side connections from/to supply/return pipes to manifolds were realized by T-pieces, if the splitting was necessary. The T-piece was put together from several fittings by using the plumber grease and fibers. The manifold was connected by clamping ring, Armaflex hoses by sealed union.

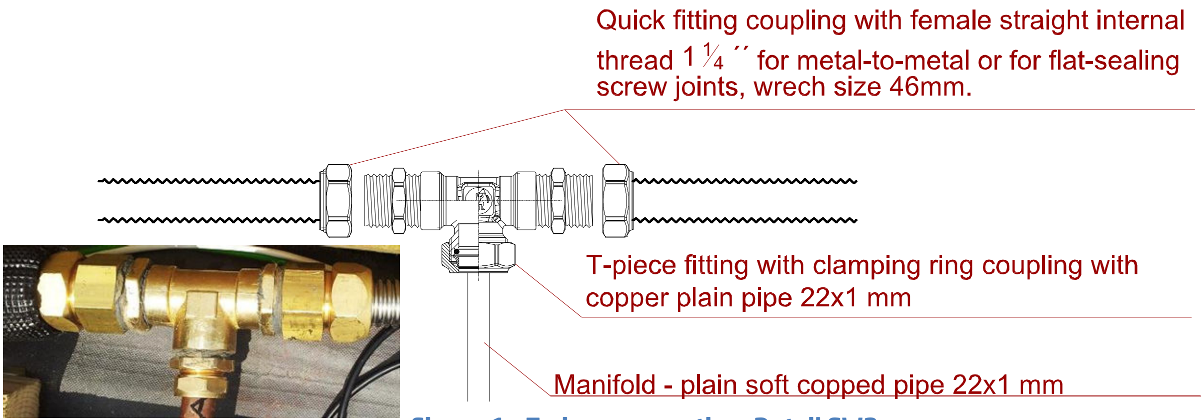


Figure 1 - T-piece connection, Detail SW3

5.2.3.2 *Balancing valve*

The pressure losses were too uneven over the array A thus the valves MSV BD, DN 25 were placed among panels in column 1 and 2. The valves were chosen with respect to size of handle to fit in gap below the roof cladding. It was also possible to take the handles away from body of valve. The setting of 6 balancing valves (seen on drawings SW-001, Appendix U) was stated during testing with sophisticated tool TA SCOPE. The right setting was found "manually" by adjusting the handles while the flow rate was measured. The particular flow rates corresponded with desired mutual division of the flow in the array rows, seen in chapter (calculation of the flow rates).

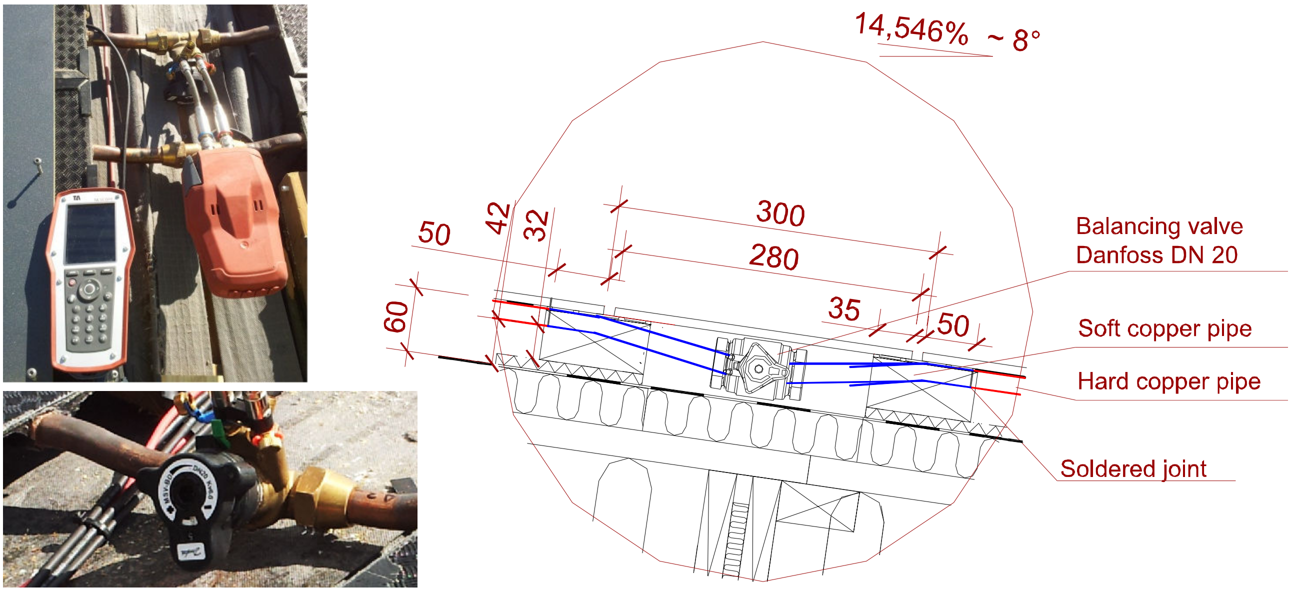


Figure 33 - Danfoss balancing valve, Detail SW2

5.2.3.3 *Supply/return piping*

For supply and return pipes were used the stainless steel corrugated pipes (hoses) Armaflex Duo Solar VA DN25 mm. Pipes led below PVT panels or roof cladding and in cavity below cladding of external wall. Pipe external diameter was 32mm and 60mm was external diameter including insulation. System union nut had 1 ¼´´female threat, wrench size 46. All piping to the PVT´s was routed with a slope to the drain back tank.

Where was necessary to disconnect the wall/roof elements the fitting SO-SDN25-DN25 was placed.

Figure 34 - Supply/ return piping and roof penetration

5.2.3.4 *Drain back tank*

The total volume of piping in PVT panels, supply/return pipes and connection pipes was calculated as almost 75 liters. That volume had to drain in the Drain back tank when the circulation pumps went off, conversely when the system run the water was lifted to the upper piping. Some buffer volume was needed to allow temperature volume span and to avoid airing the pumps when the air was sucked. Total volume of drain back tank was stated as 100l. The water level was observed through side check glass. The tank was thermally insulated with 50mm of Armaxlex AF just on site after testing period. According to the drawing below was manufactured the drain back tank.

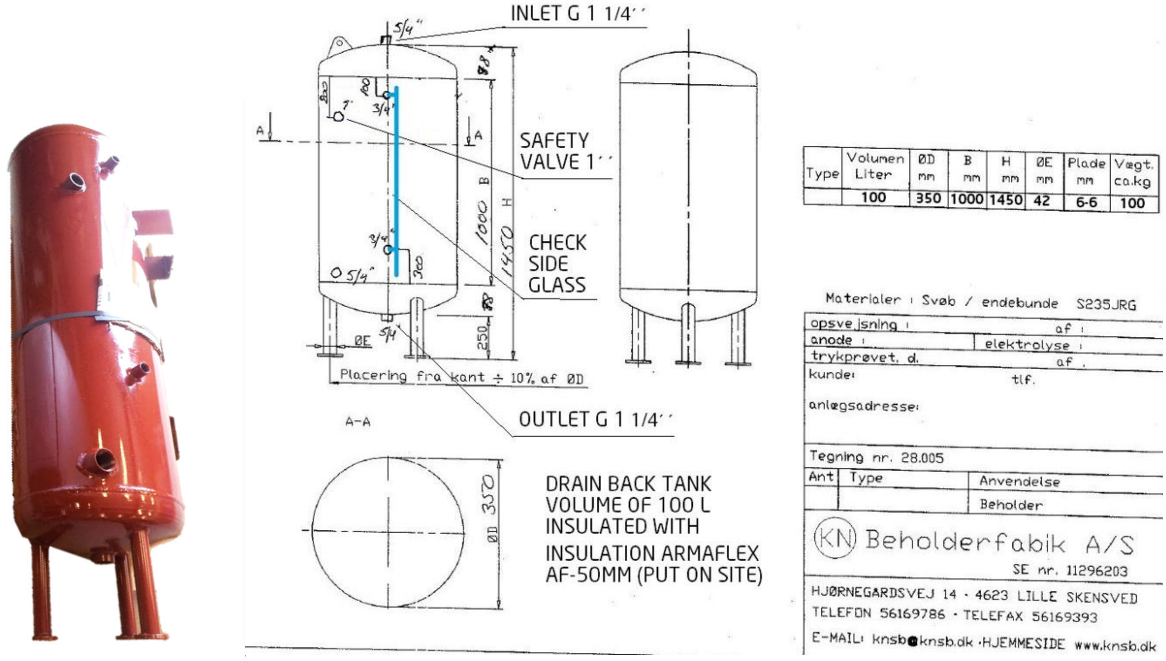


Figure 35 - Drain back tank

5.2.3.5 *Protection frame of PVT*

The architectural concept counted on subtle structure of PVT but during the construction process was necessary to add aluminum moldings protecting the glass edges against hits and spreading the stress from lifting belts during craning. Production drawings with details and piece list are seen in Appendix K.

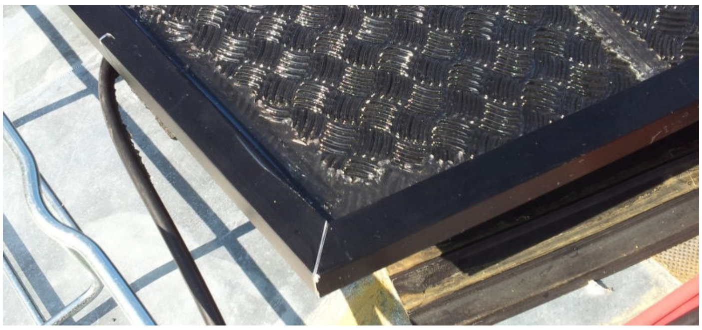


Figure 36 - Protection moldings

5.2.3.6 *PVT montage*

PVT panels were lifted by crane and placed on wooden laths following the slope of the roof. Laths then became simple supports with span on 1890mm. PVT panels were supported in the middle by

spots made of XPS (expanded polystyrene). The left cavity between PVT and roof underlay was in average 30mm thick; thickness was variable because of the piping system.
Metal holders fastened the PVT´s to the wooden laths through rubber belts with screws fixing the frame of PVT; ~300mm spacing.

Figure 37 - Supporting spots and PVT holders

5.2.3.7 *Panel temperature sensors*

Control of the PVT system was based on temperature set points. The panel temperature was measured with resistance temperature detector with temperature range -50°C ÷150°C. Each sensor was glued directly on the PVT back side between the copper pipes and in the middle of the panel lengthwise as is seen in Figure 38. In that place is expected the most even temperature division due to the copper absorber incorporated just below the covering tedlar foil. The thermal insulation covered the backside with the temperature sensors.

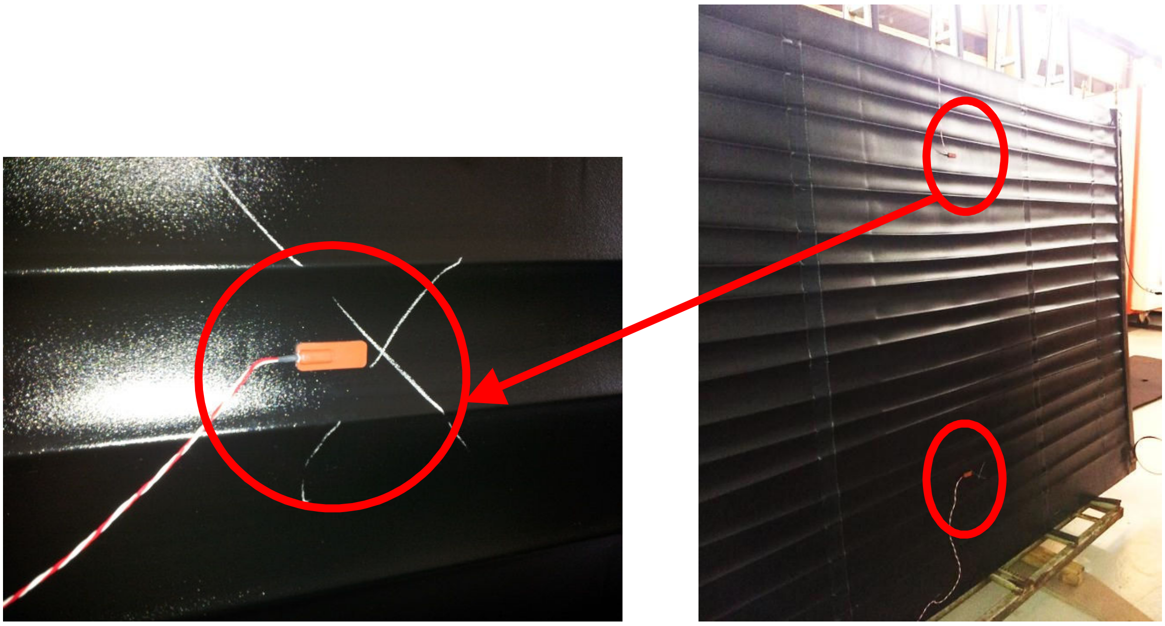


Figure 38 - Placement of temperature sensors on panel A2-3

From the overall view there were placed 4 temperature sensors in the PVT arrays: 3 in array A and 1 in array B. Surface temperature corresponded to the flow rate division over the rows of panels. As is seen on Figure 38 the sensors have been placed in order to calculate the average temperature for each independent loop (A or B).

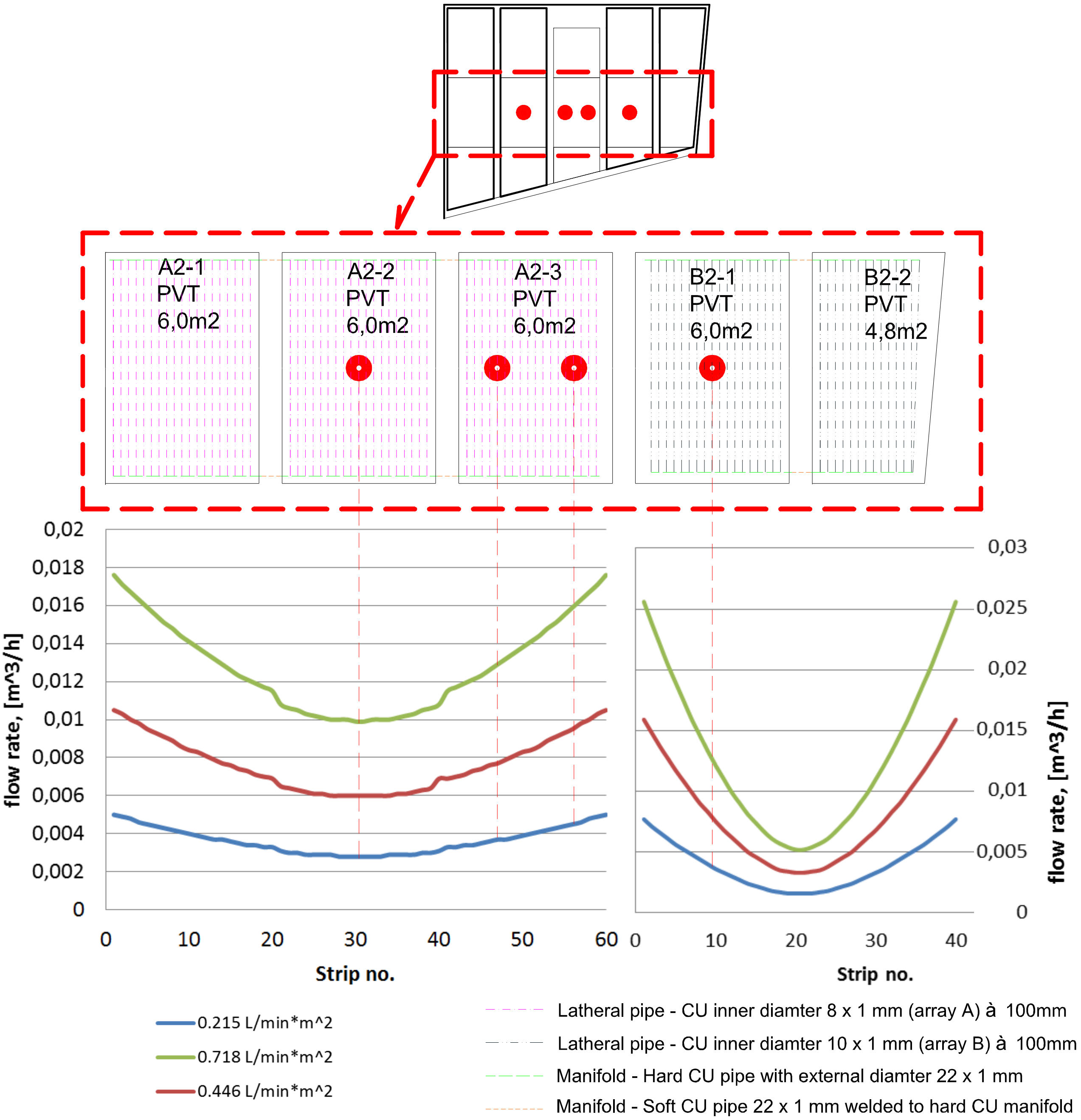


Figure 39 - Temperature sensors placement

5.2.3.8 *Insulation material*

The highest temperature of the PVT panel; stagnation temperature of 105°C; was calculated to select the right insulation material, seen in Appendix I. Other physical properties of insulation AF are nonabsorbent and self-extinguishing.

5.2.4 Realization phase

The customized modules were created without the need for a frame encapsulating the modules. The reason for not adding any frames to the modules was decided due to the overall uniform concept and reduction of the shadow losses. Lately the PVT modules were protected with moldings specially made for this purpose from aluminum under the norm EN 10327.

The PVT modules were mounted on a substructure consisting of wooden laths. The holders were the bended z-profiles made from galvanized steel and were fixed with spacing of 500 mm along the PVT modules. For further information regarding the moldings see drawing: PV041 and PV051. The external cladding was placed among in level of PVT panels where covered mutual panels connections and supported the uniform building integrated look.

Realization of PVT panels was planned to be on a turnkey based order to the manufacturer. But for manufacturer was challenging to follow strictly the drawings and the *PVT team* could not supervise during the realization. Moreover the manufacturer did not want to take full responsibility for piece lists made by *PVT team* and discussions due issues of lamination procedure or mutual joints between neighbor's panels delayed the production. Leadership of Team DTU decided to produce the piping on their own in workshops of DTU, building 119.

The author got professional support by plumber to make part of the soldering and piping in FOLD house. Furthermore, also student's workers made the manual work. In total it was spent 577 hours thereof 369 unpaid hours worked by the author. List of shifts, list of material and workflow step by step is briefly documented in Appendix J, K.

5.2.5 Simulation tools

As a simulation tool were used two commercial software's TRNSYS and PVSYST. The results from both were compared and with only one went on to continue.

"**PVSYST** is a PC software package for the study, sizing, simulation and data analysis of complete PV systems. It is suitable for grid-connected, stand-alone, pumping and DC-grid (public transport) systems, and offers an extensive meteorological and PV-components database. This software is oriented towards architects, engineers, and researchers, and holds very helpful tools for education. It includes an extensive contextual Help, which explains in detail the procedures and the models used.

TRNSYS is an open-ended transient systems simulation program with a modular structure. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. TRNSYS is well suited to detailed analyses of any system whose behavior is dependent on the passage of time. TRNSYS has become reference software for researchers and engineers around the world. Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells."
http: //www.appropedia.org/Solar_photovoltaic_software

On closer comparison of the two above-mentioned programs was found that the PVSYST program has annual energy production by about 23% higher than the TRNSYS. It was decided to continue only with the results of the program TRNSYS since the inputs were much more concrete in compare to the other program, and specific control logic of the whole FOLD control system was incorporated into the calculation model in TRNSYS. Moreover, with lower energy production is made possible to commit a so-called mistake on the safe side.

The results of PVSYST simulation can be seen in Appendix D. (*Team DTU, 2012*)

The tapping profile was implemented for a single family with shower use from EN 15316-3-1: 2007, seen in Appendix B. With this profile, daily energy needed for DHW was 5.845 kWh.

The TRNSYS simulation inputs and annual results both for Madrid and for Copenhagen are seen in Appendix F (*Kazanci, O.B., Skrupskelis M., 2012*)

5.3 Environmental impact and system treatment

This calculation explains the time needed for the PVT installation to generate the el. energy used to construct all of its components, for typical annual solar irradiation and temperature conditions of Madrid and Copenhagen.

- PVT annual el. production in Madrid (Copenhagen) is **11 391 kWh** (**7434 kWh**)
- **107 771 MJ** (29 919 kWh or 1558,28 MJ/m^2) of primary energy used to construct 1266 kg of PVT panels. About 50% of inbuilt energy was accumulated in the PV cells.
- **6985 kg of CO_2** equivalent (101kg CO_2/m^2) to Global Warming Potential was inbuilt to PVT
- The value includes also transport of PVTs panels to the building site.
- Recycling process is rejected due to very monolithic construction of PVT panels. Layers are mutually laminated with EVA material. (*Wiedemann M, 2012*)

Spain

Saved emissions for each generated kWh is **0,294** (**Kg CO_2** / **kWh**) for Spanish electrical mix (weight average of pollution emitted from various energy sources used in Spanish power plants). *(Europe Energy 2010 - Country Factsheets)*

Energy payback time :

29 919 kWh/ 11 391 kWh = **2,6 year**

The CO_2 annual reduction :

11 391 kWh/year * 0,294 Kg/kWh = **3 349 kg/year**

The CO_2 payback time :

6985 kg $CO_{2\ eqv}$/ 3349 kg $CO_{2\ eqv\ per\ year}$= **2,1 year**

The PVT panels starts to be energy beneficial after 2 years and 6 weeks. After 2 year and one month its production replaces the same amount of CO_2 equivalent as was emitted during its production. The annual CO_2 savings then are 3, 35 tons of carbon dioxide per year for the typical Madrid conditions.

Denmark

Saved emissions is **0,611 Kg CO_2** per each kWh generated by PVT for Danish electrical mix (weight average of pollution emitted from different energy sources in Danish power plants).

Danish electricity mix : 23,7 million ton CO_2 Eq. to 38,8 TWh of electricity produced in Denmark per year. *(Europe Energy 2010 - Country Factsheets)*

Energy payback time :

29 919 kWh/ 7 434 kWh = **4,0 year**

The CO_2 reduction :

7 434 kWh/year * 0,611 Kg/kWh = **4 542 kg/year**

The CO_2 payback time :

6985 kg $CO_{2\ eqv}$/ 4542 kg $CO_{2\ eqv\ per\ year}$= **1,5 year**

The PVT panels starts to be energy beneficial after 4 years. After 1 year and 5 months, its production replaces the same amount of CO_2 equivalent as was emitted during its production. The annual CO_2 savings then are 4,54 tons of carbon dioxide per year for the typical Copenhagen conditions. In the Appendix Q is seen the life cycle assessment *(Wiedemann M, 2012)*

5.3.1 Maintenance and cost estimate

PVT system is not different in maintenance point of view from the solar thermal systems. Circuits are kept in overpressure of about 1 bar thus regular check of pressure at least once a month is recommended. Using air filling in the Drain back tank can cause corrode the pipes over time so could be better to use nitrogen instead.

If the glass surface gets dirt can be washed with water and sponge. Walking on the modules is forbidden.

The manufacture provides a warranty for 10 years on a product and a performance guaranty for 26 years.

5.4 Benefits of additional cooling

To provide more universal comparison of the different solar system solutions a new calculation was carried out. Under the same surrounding conditions, similar to STC, the 3 systems with the same active area of 67,76 m^2 were compared:

- **PV panels** Photovoltaic part of FOLD PVT without thermal part and un-insulated.
- **PVT panels** "Unglazed" photovoltaic thermal panel used on FOLD house.
- **Solar thermal p.** "Unglazed" solar thermal panel. The same construction as PVT with back side insulation and passive cell.

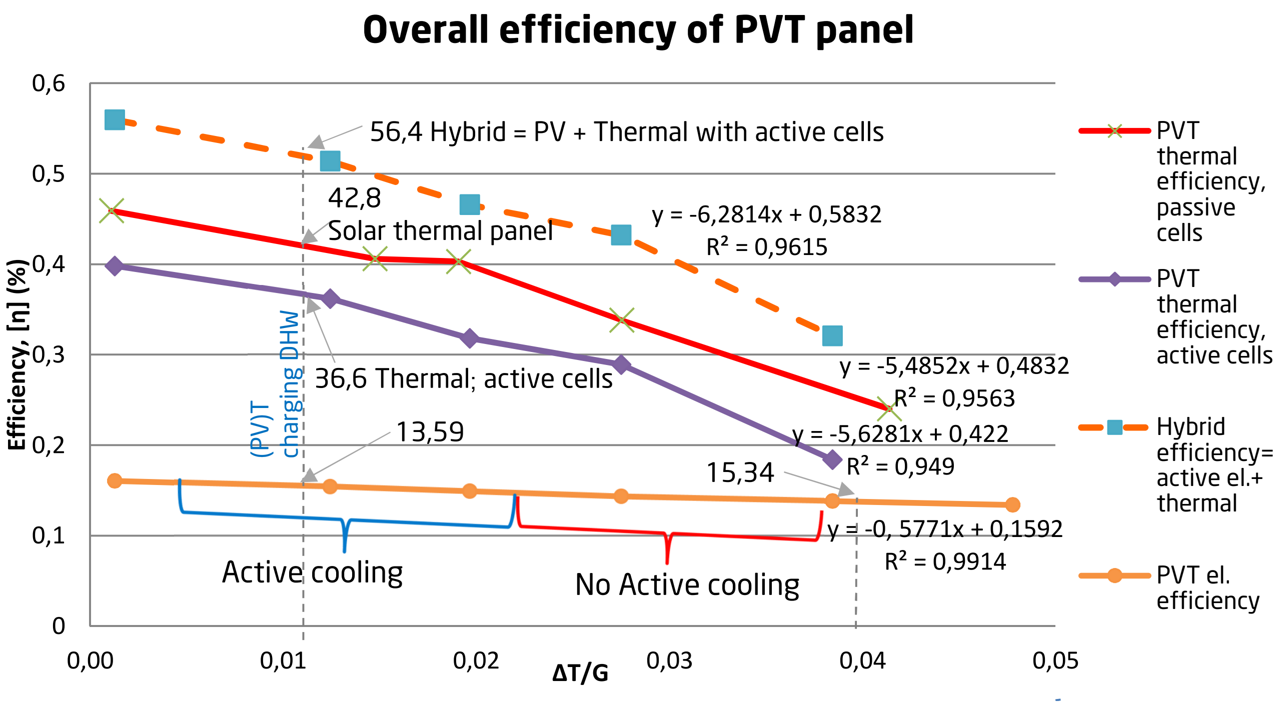


Figure 40 - Overall efficiency of PVT panel

The Chart above summarizes results of the thermal and electrical testing of final PVT panel A3-2. The hybrid efficiency curve represents the simultaneous operation of thermal and electrical part in relation to the conditions of the surrounding. As is marked on the electricity efficiency curve the Active cooling ensured higher electrical production by providing better thermal conditions for the PV cells when was directly used to supply heat to DHW tank.

Introduced was a new level of hybrid efficiency raising up to 58% of utilized solar energy that incidence with the FOLD roof top.

The **PV** panel was exposed to conditions similar the STC: Ambient temperature 25°C, 1000 W/m^2 solar irradiation, wind speed below 1 m/s was cooled only naturally and the panel temperature reached 65°C.
The **PVT** worked in mode DHW tank heating since this scenario was found as more common compare to ground cooling mode. The mean panel temperature; 35°C; was chosen as a middle temperature between DHW set point and cold water temperature. The temperature increase by passing PVT was 10K.
For the **Solar thermal** panels were used identical conditions as for PVT but it is efficiency was higher due to the non-active cells that would absorb share of solar irradiation.

Table 7 – Energetic comparison of different solar solutions

Unit	Variable	PV panel	PVT (Charging DHW)	Solar thermal	Comparison PVT - (PV+T)	
m^2	A (active area)	67,76	67,76	67,76	-	
°C	Tin	-	30	30	-	
°C	Tout	-	40	40	-	
°C	Tp (mean temperature)	65	35	35	-	
m^3/h	Flow rate	-	1,42	1,42	-	
W	Pump power	-	140	140	-	
%	Electrical eff.	13,59	15,34	-	1,75 11,4%	Static calculations based on STC
W	Electrical output (incl. losses 7%)	8564	9666	-	1102 12,9%	
%	Thermal efficiency	-	36,6	42,8	6,2 -17,1%	
W	Thermal Power (No heat losses)	-	24800	29001	-4201 -17,1%	
W	Therm. Power (with heat losses)	-	20984	25185	-2841 -17,1%	
%	Heat losses percentage	-	15%	13%	-2,3 %	
Wh	El. energy used for running the circulation pump Pump5 to fully charge the DHW tank to 60°C	-	62,9	52,4	10,5 16,8%	
$L/min/m^2$	Flow rate	-	0,52	0,52	-	
L/min/ arrays	Flow rate	-	35,24	35,24	-	
W [W/m^2]	Net Electrical balance for STC (El. generated + Heat produced/COP - El. consumption of PVT circulation pump)	8564 [126]	15924 [235]	7538 [111]	-178 (1%)	
kWh/ year [$kWh/m^2{}_{year}$] "kWh/kW"	Net annual el. energy balance for **Copenhagen** (El. generated + Heat produced/COP - El. consumption of PVT circulation pump per year)	**7214** [106,5] "784"	**7434 + 242 *** [109,7+3,6] "834"	**259*** [3,8] "28"	203 2,6%	Based on weather data
kWh/ year [$kWh/m^2{}_{year}$] "kWh/kW"	Net annual el. energy balance for **Madrid** (El. generated + Heat produced/COP - El. consumption of PVT circulation pump per year)	**10970** [161,9] "1192"	**11393 + 495*** [168,1+7,3] "1292"	**530*** [7,8] "57,6"	388 3,3%	

***Heat transferred to electricity in a way, how much el. would be used to charge the 180l DHW to 60° with a heat pump(COP 3,28 for heating); Counted with 9,2 kWp utilized from 10,8 kWp installed.**
STC conditions: Ambient temperature 25°C, 1000 W/m^2 solar irradiation, wind speed below 1 m/s.

There is seen mutual comparison of variables marked "in boxes" for different system solution in the last column of Table 7.
The efficiency of electrical generation was found 1,75 % (12,9% relatively) higher even the PVT produced hot water with outlet temperature 40°C in compare to the PV panels.
Conversely, the simple solar thermal panels performed better than hybrid PVT panel. They had better efficiency and lower heat losses that consequence less electricity used within shorter period to charge fully the DHW tank.

The **Net Electrical balance** compared all 3 systems as entirely integrated in to the house scheme. The produced heat was theoretically transferred into the electricity load as a substitute for the same amount of heat produced by heat pump air to water, coupled to the DHW tank. The electricity as energy was clearly ratable in compare to heat that would be difficult to economically compare with other energy replaced. The electricity used by circulation pumps affected the balance also. In total the balance for PVT and PV+T was almost the same.

The Net annual electrical energy balance was performed dynamically with 1-hour step and with weather data for Copenhagen and Madrid. Presented results were found by analyzing the TRNSYS simulation results. (*Kazanci, O.B., Skrupskelis M., 2012*)
In general, due to the geographical location the energy production is significantly higher in Madrid, electrical energy by 34% and heat production by 51%. Another link was found between the electrical and thermal part of PVT panel. In warmer climates, the efficiency of PVT increased in relation to separate PV and Solar thermal systems. The Net annual electrical energy balance became more positive in Madrid than in Copenhagen, from 2,6% to 3,3%, since the heat production was more than doubled.

Economically were compared the 3 aforementioned technological solutions in a way that only the roof elements were taken into account of whole system components since FOLD, even less than net zero energy house, used both of the renewable energies generation (heat, electricity) and the facility systems used would be the same.

The active arrays for all 3 systems were the same, 67,76m2. More than one theory, how the division would be correct, can be found: according to the mutual efficiency, according to the need for the various energies. Thus, the scenario with combination of PV panels and solar thermal panels within the actual roof area would have to be fair.

The costs of specific components for all 3 technologies are seen in Appendix K.

Table 8 - Economical comparison of different solar solutions

Unit	***Variable***	***PV panel***	***PVT*** *(Charging DHW)*	***Solar thermal (T)***	*Comparison* ***PVT - (PV+T)***
kWh/ year *[kWh/ m²year]*	***Net annual el. energy balance*** *for* ***Copenhagen*** *(El. generated + Heat produced/COP - El. consumption of PVT circulation pump per year)*	***7214*** *[106,5]*	***7434 + 242**** *[109,7+3,6]*	***259**** *[3,8]*	***203*** *2,6%*
kWh/ year *[kWh/ m²year]*	***Net annual el. energy balance*** *for* ***Madrid*** *(El. generated + Heat produced/COP - El. consumption of PVT circulation pump per year)*	***10970*** *[161,9]*	***11393 +495**** *[168,1+7,3]*	***530**** *[7,8]*	***388*** *3,3%*
Euro	*Amount of money saved annually (**Denmark**)*	2151,2	2289,0	77,2	60,5
Euro	*Amount of money saved for 20 years(Denmark)*	43024	45779	1544	1210
Years	*Simple payback time (Denmark)*	9,8	14,9	188,8	-72,0
Euro	*Amount of money saved annually (**Spain**)*	2149,0	2328,9	103,8	76,0
Euro	*Amount of money saved for 20 years(Spain)*	42980	46577	2076	1520
Years	*Simple payback time (Spain)*	9,8	14,6	140,4	-51,6
Euro	*Mass production cost (more than 100 repeated)*	21 065	34 040	14 578	*-1 603* *-4,7%*
DKK	*Mass production cost (more than 100 repeated)*	156 500	252 900	108 306	*-11906* *-4,7%*

Price in Euro per kWh of Electricity for annual consumption 3500kWh ± 25% ***0,298 €/kWh Denmark****;* ***0,196 €/kWh Spain*** in May 2012; Exchange rate ***7,429 DKK/Euro.***
**Heat transferred to electricity in a way, how much el. would be used to charge the 180l DHW to 60° with a heat pump(COP 3,28 for heating)*

The price of the pilot PVT installation with all its components was 665 149 DKK; 89 534 Euro; 9617 DKK/m^2; 1295 Euro/m^2. When the FOLD installation would be 100 times repeated this cost would drop to about 40%. *(*Taul P., Nielsen M. H.,2012*)*

Table 9 - Price level characteristic of Photovoltaic thermal system

	DKK (€)	DKK/m^2 (€/m^2)	DKK/kWp el. (€/kWp el.)
Pilot installation of PVT system incl. all components	665 149 (9617)	9 617 (1295)	61 587 (8290)
100 times repeated installation of PVT system incl. all components	269 006 (36210)	3 890 (524)	24 908 (3353)

Exchange rate *7,429 DKK/Euro.; 10,8 kWp installed*

This price assumes all components for market prices even most of the material was sponsored. Price can be compared with very similar product of Turkish company Solimpeks® called Power Volt (seen in Appendix O Solimpeks) . The obtained price for a bulk purchases would be about 24% lower; 2514 €/kWp or 334 €/m^2.

5.5 Conclusion and discussion

Energy

This result was quite surprising since the hybrid PVT system produce annually slightly more energy with half size of active area in compare to independent thermal and photovoltaic systems. By other words, the PVT really managed to combine the two technologies with slightly improved overall efficiency with half of area as if both technologies would work separately on area twice as big.

PVT uses most of the components, material and space of house envelope together what save the space and the decreases cost of PVT according to the price of two separate systems that would produce same amount of energy. This makes the PVT more attractive.

Obviously, this statement works only if are compared similar technologies such as "unglazed" solar thermal panels and PVT used in FOLD. To compare different technologies, as a "glazed" solar thermal panels and PVT used on FOLD would desire to develop feasible key (logic) how to compare technologies with different product prices, efficiencies, etc...

The efficiency of photovoltaic cells decreases with increasing cell temperature. This is described by the power temperature coefficient that was the same for PV and PVT since the used cells were identic. The active cooling of photovoltaic cells realized in PVT influenced the electricity production positively but less than was expected. Clarifications of smaller increase of electrical production in general and also between Denmark and Spain can be three. Firstly in the northern climate is often seen lower air temperature with the same solar irradiation as in the south, thus in Copenhagen the electricity production is less influenced by high temperatures. Secondly, reason is the surplus of heat in Madrid. The DHW tank gets already fully charged during period when the house is still "free" cooled by the borehole. House cooling has higher priority thus the PVT´s are waiting. They are not cooled by semi-cold water from bottom of DHW tank and neither by borehole. The PVT´s temperature rises and the electrical efficiency decreases. Thirdly, the actual efficiency of PVT´s used on FOLD is a prototype with several detected failures, seen in Appendix M.

Economy

The "*Amount of money saved annually*" represented the amount of money that would user pay for buying from grid the certain amount of electricity generated by renewable energy.

In the Table 8 is seen economical comparison for PVT and combination of PV and Solar thermal systems considered in Denmark and Spain.
The ration between PVT and PV+ Thermal collector kept obviously the same as for energy balance. The PVT´s saved annually 60,5 Euro more what means 2,6% for Denmark and similarly for Spain; 76 Euro and 3,3%.

The absolute amount of money saved in Denmark and Spain were almost similar, just 1,7% higher saving in Spain In contrast to the amount of extra 34% of generated energy. This similarity was caused by almost 1/3 higher energy price in Denmark then in Spain. Thus the renewable energy is more worthy rewarding in Denmark with the same investment cost.

Product considered price was for a mass production with 100 repetition of FOLD system size. The cost of PVT panels was 4,7% lower than for 2 separate systems.

Very important market aspect is the payback time what inform those interested in after how long time the machinery pay itself and start to make money. The calculation used the current prices (May 2012). The "*simple payback time*" did not consider the inflation, rise of energy prices during the system lifetime what harmed the "Amount of money saved for 20 years", and extend the payback time according to the tendency in last period.
The payback time for PVT was less than 15 years in both countries. The PV collectors had shorter payback time what indicates the margin role of the PV part in PVT panels. The standalone Thermal part was very poor as a heat producer. For the comparison of payback time was used following equation:

$$PVT - PV - Th$$

$$PVT_{payback} - PV_{payback} \cdot \left({PV_{investment}}/{PVT_{investment}} \right) - Th_{payback} \cdot \left({Th_{investment}}/{PVT_{investment}} \right)$$

In this category was PVT significantly better but from engineering point of view is usage of such a solar thermal system implausible. The aforementioned result shows such a thermal part as non-sustainable solution without junction with PV cells cooling.

The shorter payback time o PV in compare to PVT but higher total savings of PVT before PV system tells that the solar thermal part of PVT is too expensive according to the extra yield of heat that brings and the effect on PV production. The solutions how to achieve same payback time as PV are two:

- Produce PVT panels 33% cheaper than currently or other way cheaper by cumulated savings within 10 years. The cost of thermal part can not overlap 11,4% of the rest of the PVT panel in context with the positive effect of cooling to the PV production; 11,4% relatively and 1,75% absolutely.
- Increase the relative energy efficiency by 33% according to the current PVT panel.

Important fact is also that aforementioned values have been carried out for FOLD house and the annual energy balance may wary in relation to different logic and energy treatment. E.g. in FOLD house was used standardized daily water tapping profile but the cooling of indoor space was prioritized before cooling the PVT in the ground. If another source for cooling PVT´s would be used the energy balance would not be the same. Probably the best would be to couple PVT´s with another system utilizing low temperature heat, such a heat pump, absorption chiller or preheated cold-water tank. The usage of reserved borehole was not economically evaluated since in actual case it was primarily handled by space cooling but with price around 11 000 Euro for 120m deep borehole it seems non-feasible.

The conclusion is that the PVT panels performed well with substantial effect on electricity production in compare to the naturally cooled PV panels. However, there is still a room for improvement. Namely, the production cost of cooling thermal part of PVT should be realized cheaper and likely by technology that is more efficient. The source for PVT cooling should highly available and well integrated in the energy schema.

5.6 Experience of system functionality

The PVT panels were handled during several tastings, assembly, and disassembly of FOLD house. During these actions was collected lot of valuable experience that might be communicated.

Manipulation with PVT panels was delicate due to the large size and fragility of thin glass without any protection. All moving was done in vertical position, glass was laid only to put the insulation and then during mounting on the roof laths. During craning, the glass was undulating. During several accidents, the glass was smashed even just a small hit to the edge. Protection frame and thicker glass or a loadbearing frame would create much more solid element to work with.

The problem with leakage inside the lamination appeared during the system operation. The problem appeared most likely in a joint between a lateral pipe and manifold just after the panel was exposed to higher pressure than was tested after soldering. This problem was fixed with special liquid for clogging the car radiators.

When the leakage was fixed system was tight and ready to be tested. *PVT team* had difficulties to keep the flow rate stable on both pumps 3 and 5. It was found out that rising the pressure up to 1 bar helped to pumps work responsibly. For case of mistake was created additional condition in control logic saying that if the flow meter do not measure any flow for 10 seconds the pump go off and start over. This protected the pump against the damage.

The PVT panels in circuit were connected in parallel but no blocking diodes were installed to prevent the overcurrent situation when no electrical loads were connected yet. One cell in panel A2-1 become a producer, temperature raised to high and the glass locally melt down. There were also suspicions that more cells get damaged. Since it was not clear if the mistake was caused by electricians connecting or by failure of the manufacturer of the PVT panels, an insurance claim with photo documentation of "hot spots" was made, seen in Appendix M.

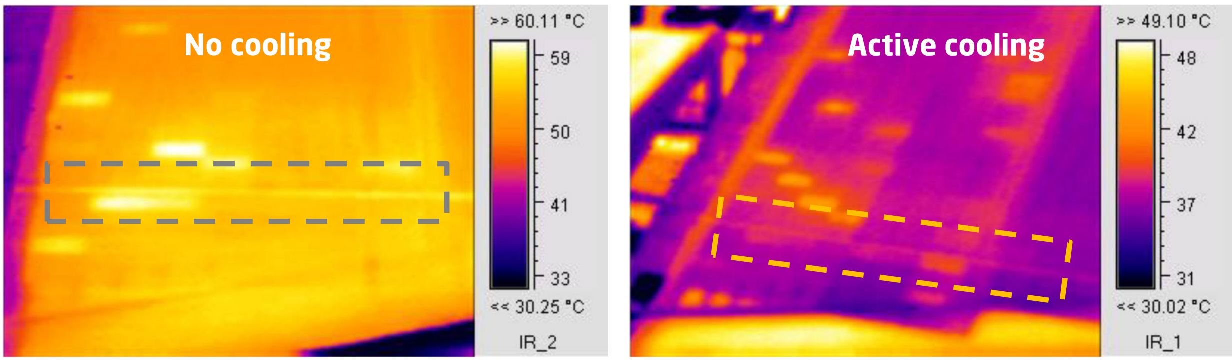


Figure 41 - Figure 30 - Thermo vision pictures of PVT A3-2

On figure above are seen some PV cells significantly warmer than the neighbor's cells without difference if the cooling was active or not.

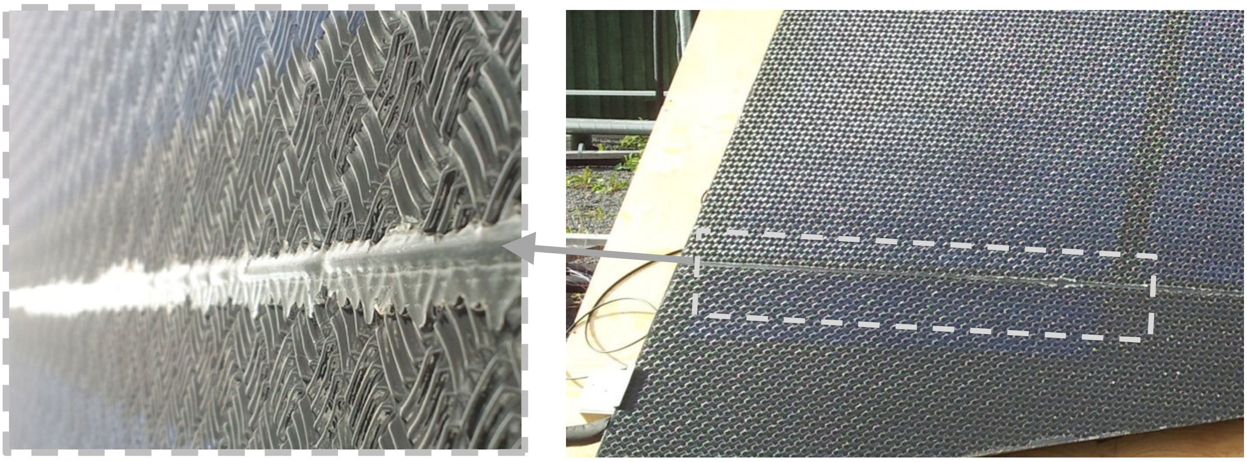


Figure 42 - Glass connection on PVT A3-2

The dashed boxes sign connection of two pieces of glass by EVA material. The temperature is obviously higher in this line what means that the EVA does not transfer the heat well.

During the disassembly period in Spain was found only on one panel (A 1-2) EVA material melted down and poured out from lamination in direction of roof inclination, seen on Figure 43. This failure was obviously caused by to high temperature around the upper manifold, where appeared the max temperature, due to lowest flow rate, as predicted. The maximal temperature probably did not pass the stagnation temperature at 105°C. The reason was not clarified yet.

Figure 43 - Melted EVA on PVT panel A1-2

A special tool list for PVT and HVAC system of FOLD house was done. It is seen in Appendix N.

5.7 Further investigation

Idea of PVT is not new, but since near past were the technology prices unduly in this direction. Nowadays, the market situation of PVT is highly confusing. Many producers promotes mishmash of vary technologies but offers only the end product which, as is suggested in this paper, is not the key to sustain the presented increased efficiency. The way seems to be the right choice of PVT technology suitable to the coupled system. Good combination can bring the proclaimed rise of effectiveness and let the PVT to excel the advantages compare to the " conventional solutions" .

When interest do not focus on the integration of PVT in the energy concept as a whole, it will be possible to meet with the improper use of PVT when the potential is not used and the product will be overkill to the detriment of rest of the installation what can damage the reputation of PVT in general.

5.7.1 Development suggestions

- Involve testing and development in next **SDE 2014**
- Investigate is the Fin efficiency would be improved by thermal mantle absorber instead of lateral piping. Lower cost product with even lower efficiency may be in an alternative. （Consider cheeper Low-tech vs efficient but costly Hi-tech） E.g. MEFA absorber seen on Figure below.

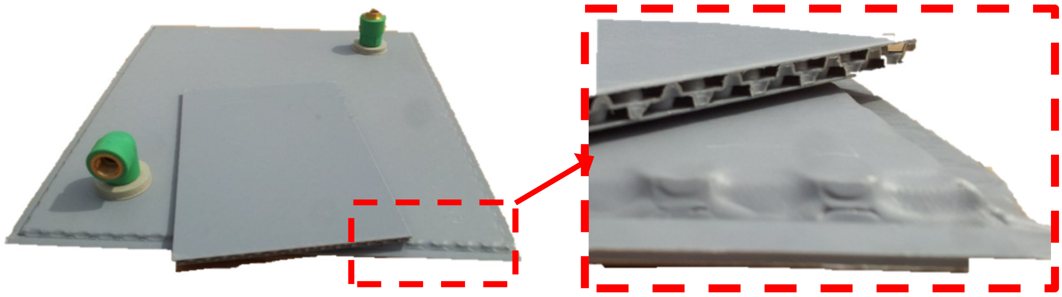


Figure 44 - MEFA unglazed thermal absorber

- Investigation of use another materials for front cover with different transmittance, emittance and heat loss coefficient.
- Consider another way of embedding the absorber to cells than lamination, different composition. Otherwise in case of broken glass is entire PVT turned to waste. Option of independent PV and Thermal part. Moreover the heat transfer of EVA material is poor.
- Take serious issue of static, compactness and easy handling of the PVT panel. Consider bearing frame and smaller size of the elements.
- Produce PVT on one place, it can reduce risk of failure
- Use PV cells with higher power temperature coefficient （%/K. The effect of cooling down the solar cells is then more significant.
- Investigate use of PV cells with high absorbance. Higher efficiency of thermal part is expected
- Filling of free space in Drain back tank with less aggressive filling than air (nitrogen)
- The pump must be located always below the minimum water level in the drain back tank
- Drain back tank system with two pumps works more responsible when is over pressurized
- Control system that decrease temperature set point id DHW if there is enough sun expected

5.7.2 Scenarios to consider

- Photovoltaic-powered heat pump to produce heat for domestic hot water or for heating a passive house by pre-heated water from PVT.
- Analyze the observed full scale data from competition in Madrid.
- Thermal and electrical measurements perform with more advanced tools that allow using tracking (zero incident angle), maximal power measurement, …
- Investigate usage of solar cooling: Couple absorption chiller with PVT system. The cooling need of the interiour follows the intensity of hot water production.
- Compare the current system where the DHW tank is charged directly with case where the preheated "cold" water tank is coupled with PVT system, not only in summer.

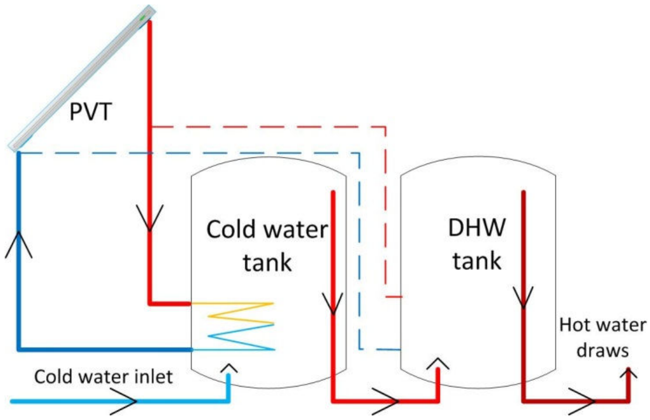


Figure 45 - Pre-heated cold water tank scheme

- PVT collector with Fresnel lens: "Collector with linear Fresnel lenses separates the direct solar radiation and concentrates it on the narrow linear absorber placed in a small focal while diffuse sunlight illuminates the inside space behind lenses. Natural lighting provided the lenses are characterized by a uniform intensity without sharp contrasts and problems with glare."

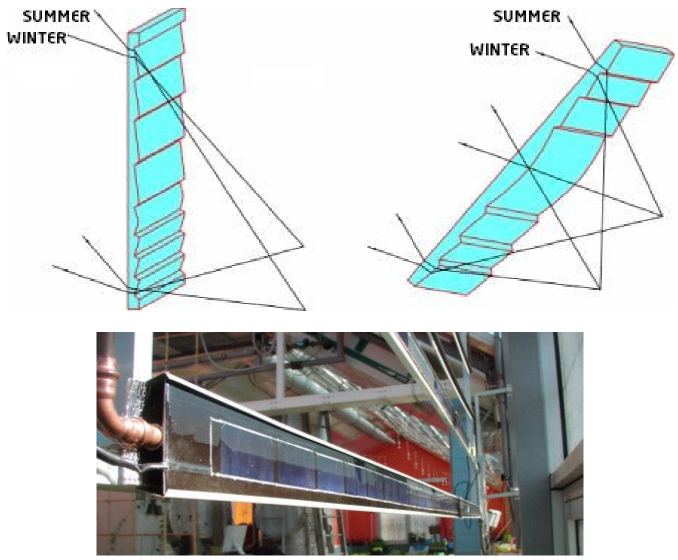


Figure 46 - Fresnel lens PVT

"The thickness of the flat lens thickness roughly equivalent to ordinary window glass is linear thus Fresnel lenses can be easily integrated into glazing windows, facades, roofs." *(Matuska, 2009)*

6. Energy consumption

6.1 HVAC

The research of energy balance was contributed to create a HVAC concept which was deeply described in (*Kazanci, O.B., Skrupskelis, M., 2012*). Then the HVAC concept was realized as seen on following scheme. The scheme is seen in a large print in Appendix U.

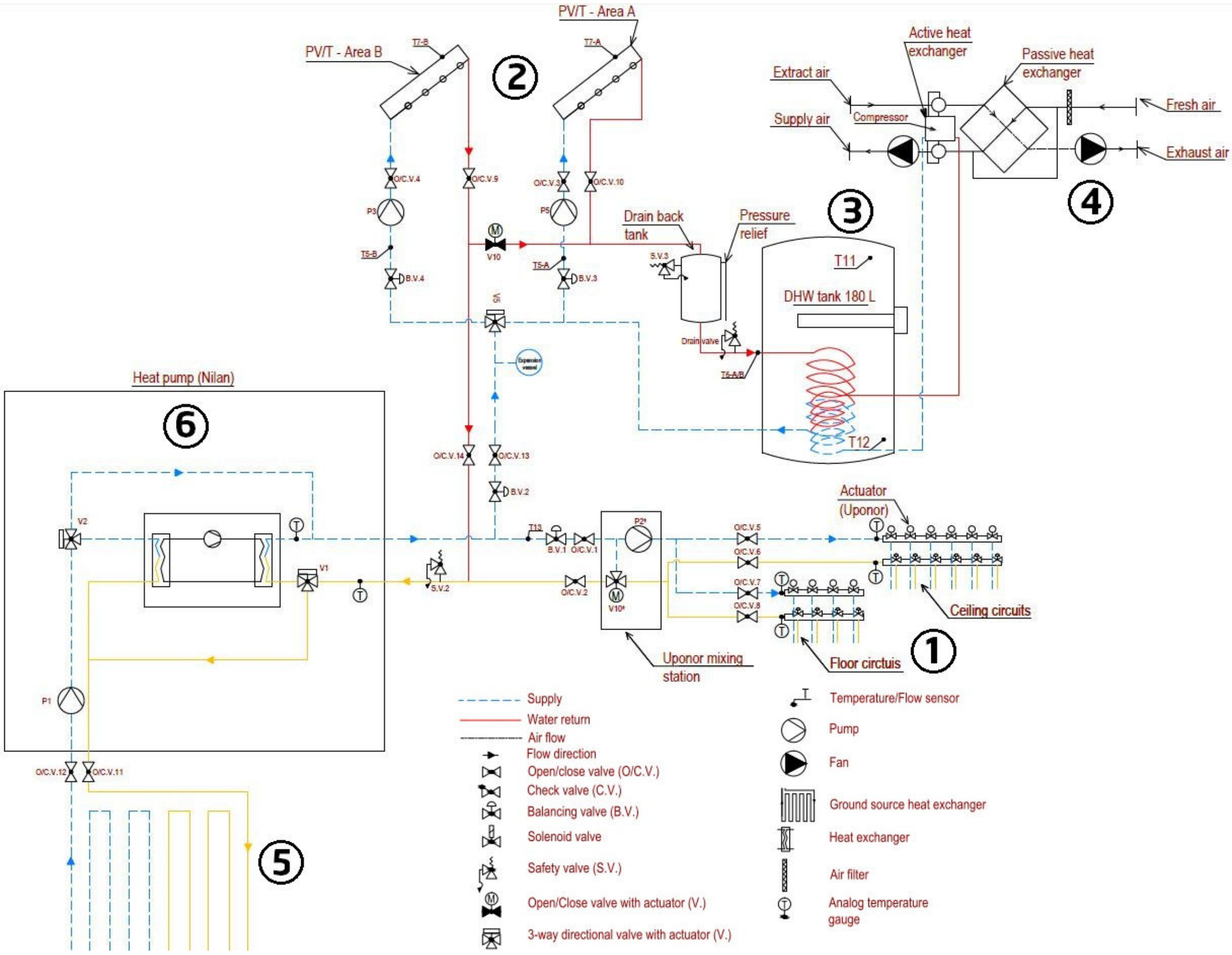


Figure 47 - HVAC scheme

The main parts of the system are:

1) **Embedded pipes in the floor and ceiling**
2) **Photovoltaic thermal system**
3) **Domestic hot water tank**
4) **Mechanical and natural ventilation system**
5) **Ground source heat exchanger**
6) **Ground coupled heat pump**

Energy rating is based on calculations of delivered and exported energy of a building for **heating, cooling, ventilation, domestic hot water and lighting**.

6.1.1 Heating / cooling

The space heating and cooling demand is supposed be covered primarily by radiant system embedded into floor and ceiling cladding (1). System was designed by DTU student from Uponor components (PEX pipes, installations plates, supply & return manifolds with actuators, mixing pump unit, room sensor…).

- Cooling source was cold water supplied directly from **Ground source heat exchanger (5)**. Cold water bypassed **Ground couple heat pump (6)** if no heating demand (free cooling) and flow to both ceiling and floor pipe system if needed. The right inlet temperature was mixed in mixing station. Designed capacity of free cooling system was 2,5kW. Supply and return temperature for floor and ceiling were 16,5/18,5 °C
- Designed heating capacity of heating system using embedded pipes in floor was 1,9kW. Supply and return temperature for floor were 34/30 °C
- Limits for indoor air temperature during competition period were 23-25°C

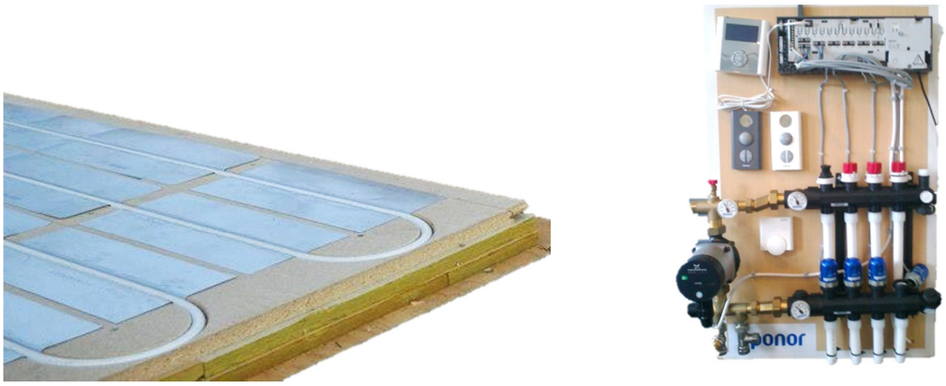


Figure 48 - Radiant heating/cooling system in FOLD

In extreme case the **mechanical ventilation (4)** supported to support space heating/cooling via inbuilt coils in Air handling unit.

The **natural ventilation (4)** overtake the role of cooling under feasible outdoor conditions via façade and roof openings.

6.1.2 Ground source heat exchanger (5)

Ground source heat exchanger either is advantages to use as energy supply for heating or as a heat sink for cooling the house or PVT´s. Embodiment with a borehole represents a low temperature mass with stable temperature in relation on depth (capacity) and ground type.

Research and development about use of the bore hole was done and documented in (*Kazanci, O.B., Skrupskelis, M.,2012*). From the literature raised following:

- Suitable is vertical single U-tube configuration within 120m deep borehole. The ground temperature in depth below 10m from the surface is assumed to be constant during the year, if the bore hole is not active, namely equal to local yearly average air temperature (14,3°C in Madrid and 8,3°C in Copenhagen with 1K fluctuation).

Table 10 - Ground source balance

Total borehole resistance	0,37 (mK/W)
Flow rate of heat transfer fluid	0,65 (m^3/h)
Heat rejected to the ground	-1550,16 (W)
Heat rejected per meter of borehole	-12,92 (W/m)

	Copenhagen	Madrid
Energy balance of the ground	-3128,8 (kWh)*	-548,6 (kWh)
Average COP	3,29 (-)	3,13 (-)
Energy balance of the ground after 10 years	-28,7 (MWh)	-2,8 (MWh)

*Negative value means more energy was extracted from ground then stored.

It was calculated that 848 kWh of electricity wound be consumed to operate the FOLD house without bore hole against 65kWh of electricity when the Bore hole drilled for reference year in Madrid.

The SDE rules forbidden to dig to the ground in Madrid thus the borehole was represented by external 500l buffer tank with inbuilt heat exchange coil cooled by additional chiller to constant temperature. Effect of this solution was proved by calculation documented in (*Kazanci, O.B., Skrupskelis, M.,2012)*.

6.1.3 Ventilation

Indoor air quality was kept in first order by **natural ventilation** if the outdoor conditions were suitable. Natural cross ventilation was provided by 2 window openings placed on opposite gables with height difference. The chimney effect of natural ventilation is increased by roof skylight with shading device.

The rest of period kept conditions **mechanical ventilation** where a fresh air was supplied from wall diffusors to the room, mixing was reached and the air was extracted from toilet and shower (kitchen hood if cooking). The heat from exhaust air could be recovered passively in cross flow heat exchanger with bypass option or actively via coils in supply& exhaust duct coupled with heat pump placed in air handling unit.

- Parameters of indoor air quality control were CO_2 level (bellow 800ppm) and relative humidity (40-55%).
- Designed air flow rate was 0,678 l/s m^2 and inlet temperature 18°C

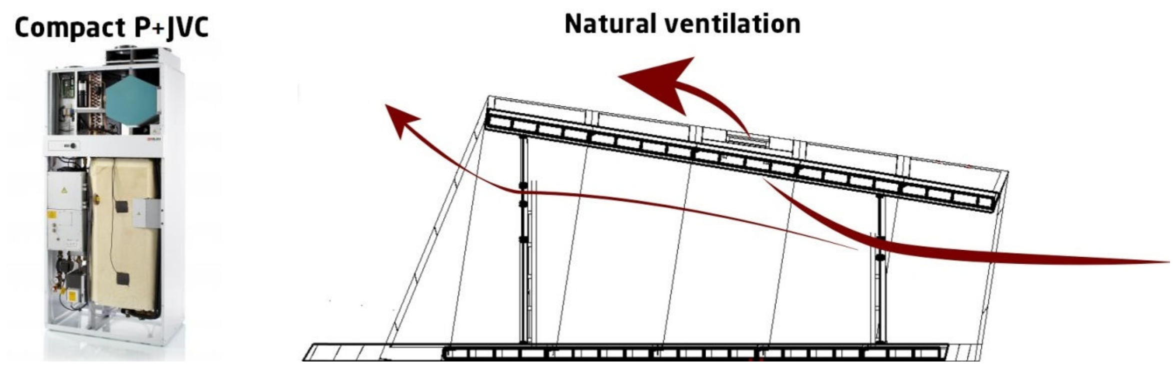


Figure 49 – Mechanical and natural ventilation

6.1.4 Compact P+JVP unit (3,4)

Nilan Compact P+ JVP (see Appendix C) is multifunctional unit that could be so-called heart of HVAC system. Unit is comprehensive ventilation and heating system saving space for installations. The unit installed in FOLD included the following features:

- Air handling unit for mechanical ventilation with active and passive heat exchanger (4)
- Hot water tank (3)
- Ground coupled heat pump (6) installed as an additional equipment

6.2 Domestic hot water

The total volume of DHW tank was 180l and the tank was equipped with 2 spiral heat exchangers and one direct heating element. Hot water was primary produced by the Photovoltaic thermal panels (corresponds with Chapter PVT Control logic 6.2.1.8) via spiral heat exchanger close to the bottom of the tank.

First back up system was HP coupled with air handling unit when the condenser was built in DHW as the second spiral and the evaporator can be any of the 2 coils in supply/exhaust duct. There is a 4-way valve used in HP.

The second back up was direct heating element, 1,5 kW, warming up the auxiliary volume of 54 l.

The control strategy is deeply described in Chapter 6.2.1.8.

6.3 Lighting

The energy for lighting was included in Energy balance simulation for purpose of the SDE competition but from the Energy Performance Certification was excluded. Explanation follows:

"The definition of energy rating says in the Note that the inclusion of electricity for households and outlets and lighting in residential buildings depends on national decision." (EN 15316-1: 2007)

"The total primary energy use in the energy frame in Denmark consists of heating, ventilation, cooling, domestic/service hot water, and lighting (except in residences). Tenants' or users' electricity is excluded." (*Risto K. and comp. May 5, 2010*)

Table 11- Lighting in the FOLD

Pieces	Product	Purpose	Power (W)	Total power (W)
1	ATELJELYKTAN 201601 Kiwi Bord LED 13W	Work station lamp	13	13
3	Fagerhult 53432 Glas Globe 1xTC-TEL 18W	Near bed	18	54
4	Fagerhult 56534-85 Discovery 1xTC-DEL 26W	Shower, toilet, wash/storage room, and tech room	26	104
9	Fagerhult 79668 MARATHON MINI HRGI MAX 35W WHITE	General lighting on light tracks in the ceiling	10	90
1	Snowflower	Above the table	18	18
11	Nordtronic Quict instal - 5W LED	Exterior lights (5 south overhang,6 north overhang)	5	55
				334

In the table (Lighting) is seen the description of realized ligting installation in FOLD house.

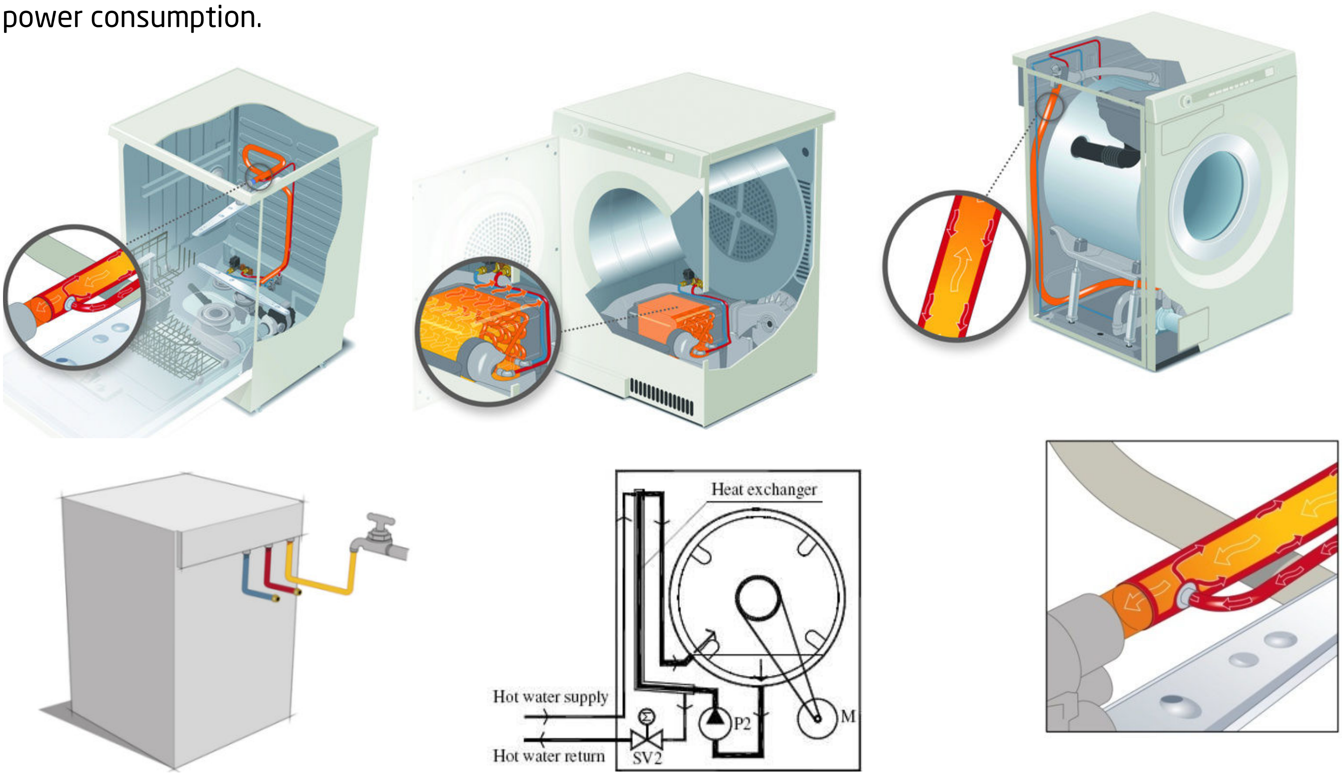
6.4 Appliances & Low energy domestic end-use

This sub-chapter was addressed to the design of home goods; low energy end-use; equipment and further energy saving proposals. The appliances fulfilled requirements given by the "Solar Decathlon Rules V5.0" for each Sub contest. The technical specifications are attached in Appendix A.

6.4.1 HWC appliances (Heating Water Circuit)

Company ASKO (Gorenje Group Nordic) has HWC solutions for laundry and for domestic use. Appliances for FOLD house are washing machine W6884 HWC, tumble dryer T784HWC and dishwasher D5654W HWC.

"Heated water circuit" supplies heat to run the appliances with a flow (min 55°C and 1,6 l/min) through a heat exchanger inbuilt in the machine, which heats up the process (potable) water or air used inside the machine. The appliances automatically regulate flow of process water (orange fluid seen on Figure 50) inside machines by pump "P2" which runs and stops to reach constant desired temperature. The heating water circulation continues until the machine has been already heated, or until the machine switches to electric heating. That happens when the temperature difference between the domestic hot water tank and the machine is too small (5 °C for the dishwasher and 7 °C for the washing machine). The heat exchanger is made as pipe in pipe when secondary water heat up counter flow water used for washing in clothes washer and dishwasher. Compact heat exchanger in a clothes dryer is water to air based. This arrangement reduces the need to operate the traditional electrical heat element what leads to a replacement of the majority of the electrical power consumption.



Yellow: *Cold potable water used for washing*
Red: *Secondary (circulation) heating water going inside the machine*
Blue: *Outgoing secondary (district) heating water after heat transfer*
Yellow to orange: *Heated potable water used for washing/heated air used for drying*

Figure 50 - ASKO HWC appliances

6.4.2 Equipment

The complete list of equipment with technical specification was created but in this section are introduced only applications that were considered worthy to mention. Full Appliances report with self-made low energy used guide is seen in Appendix A.

6.4.3 Computer

The Raspberry Pi is a credit card sized single-board computer developed in the UK by the Raspberry Pi Foundation with the intention of stimulating the teaching of basic computer science in schools. Preference of this equipment is the low power consumption (3,5W) in compare to conventional PC´s.

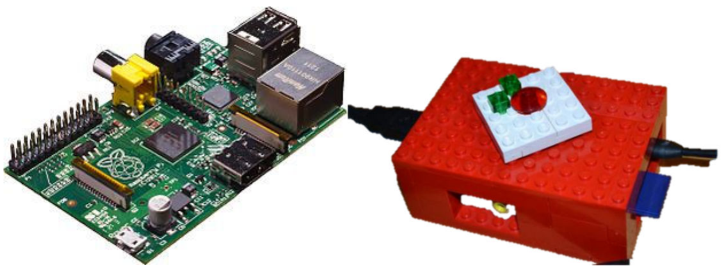


Figure 51 - Computer

6.4.4 Cookware

Traditional electric cooktops use some form of electric resistance to create heat, which is transferred to the saucepan and its contents.

Induction cooking is based on magnetic fields: each 'element' (an induction coil) generates a magnetic field that induces heat in steel cookware placed on top of it. In essence, the pot becomes the element that cooks the food, so the cooktop surface does not get as hot as other cooktops. Induction cooktops have the same instant control as gas and are the fastest of all cooktop types to heat and cook food.

Induction cooking uses 90% of the energy produced compared to only 55% for a gas burner and 65% for traditional electric ranges. Induction provides extremely fast boil and re-boil, over 50% faster than gas or electric.

The double-walled Durotherm system minimizes the energy required. The pot is closed by separate double-walled serving lid. This elegant serving combination is so well insulated that it keeps food hot for up to two hours.

Figure 52 - Double wall pot

6.4.5 Home entertainment system

The home entertainment system is not mandatory by the rules. However, for purposes of the public visits and for the required dinner party is desirable to have such a system in the house.

Because the device iPad2 by Apple has been preselected to control functionality inside the house and influence a human behavior. We decided to use the entire home system by company Apple called **AirPlay** provided through products **Apple TV** and **AirPort Express**. This way we can use only one device to browse internet (control the house based on webpage access) and control and stream multimedia we want to audio & video inside/outside the house. Likewise, the Apple systems are known as proofed and reliable working systems without unexpected failures.

The setup, seen below on Figure 53, is not a common use of the Apple systems. The components were studied individually and the final scheme was discussed with IT group of Team DTU.

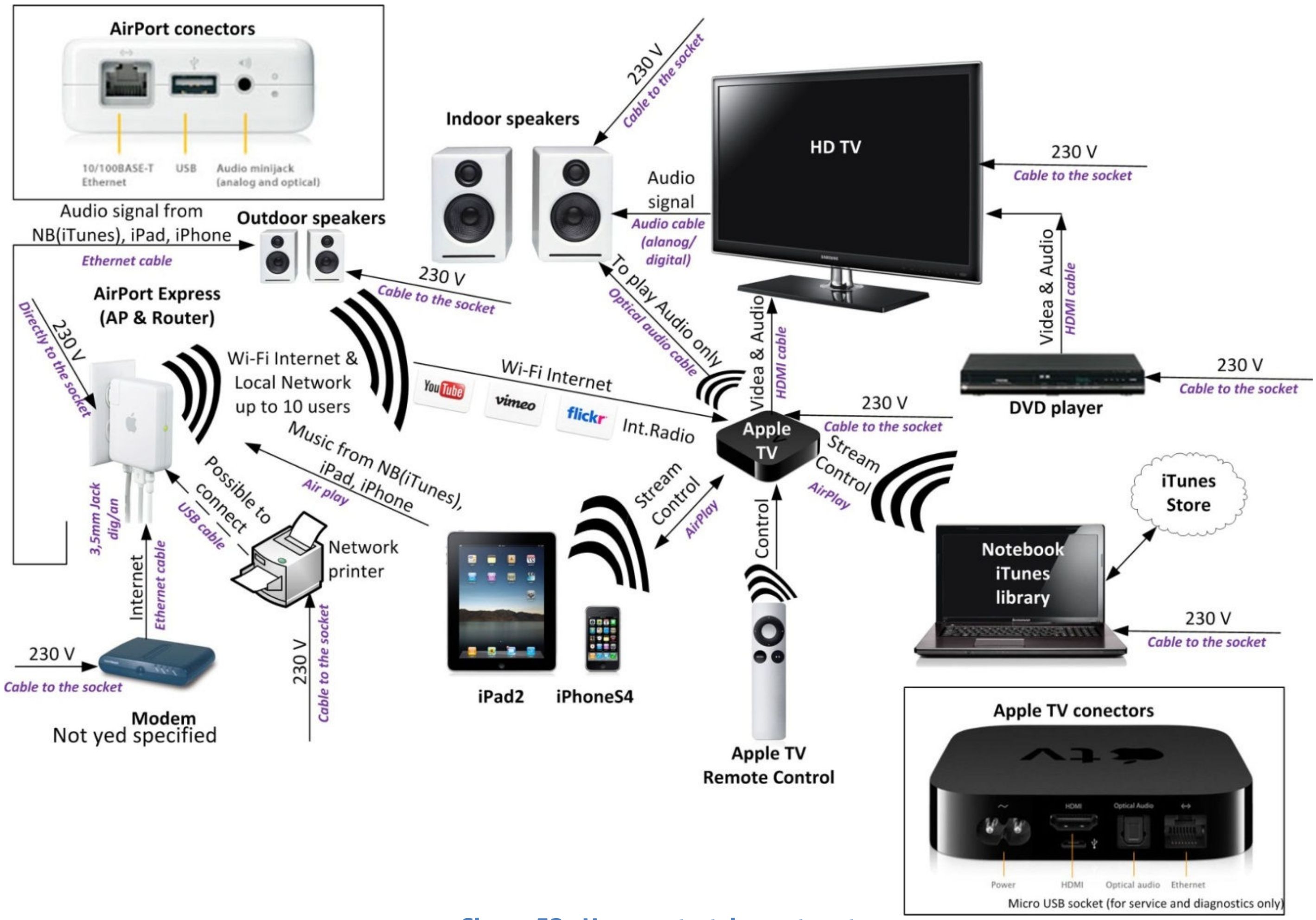


Figure 53 - Home entertainment system

6.4.6 HWC alliances in FOLD house

There were used Clothes washer, Tumbled dryer and Dishwasher with heating water circulation function (HWC) in the FOLD house. Dishwasher was integrated into the kitchen table next to kitchen sink (seen on Figure 54).

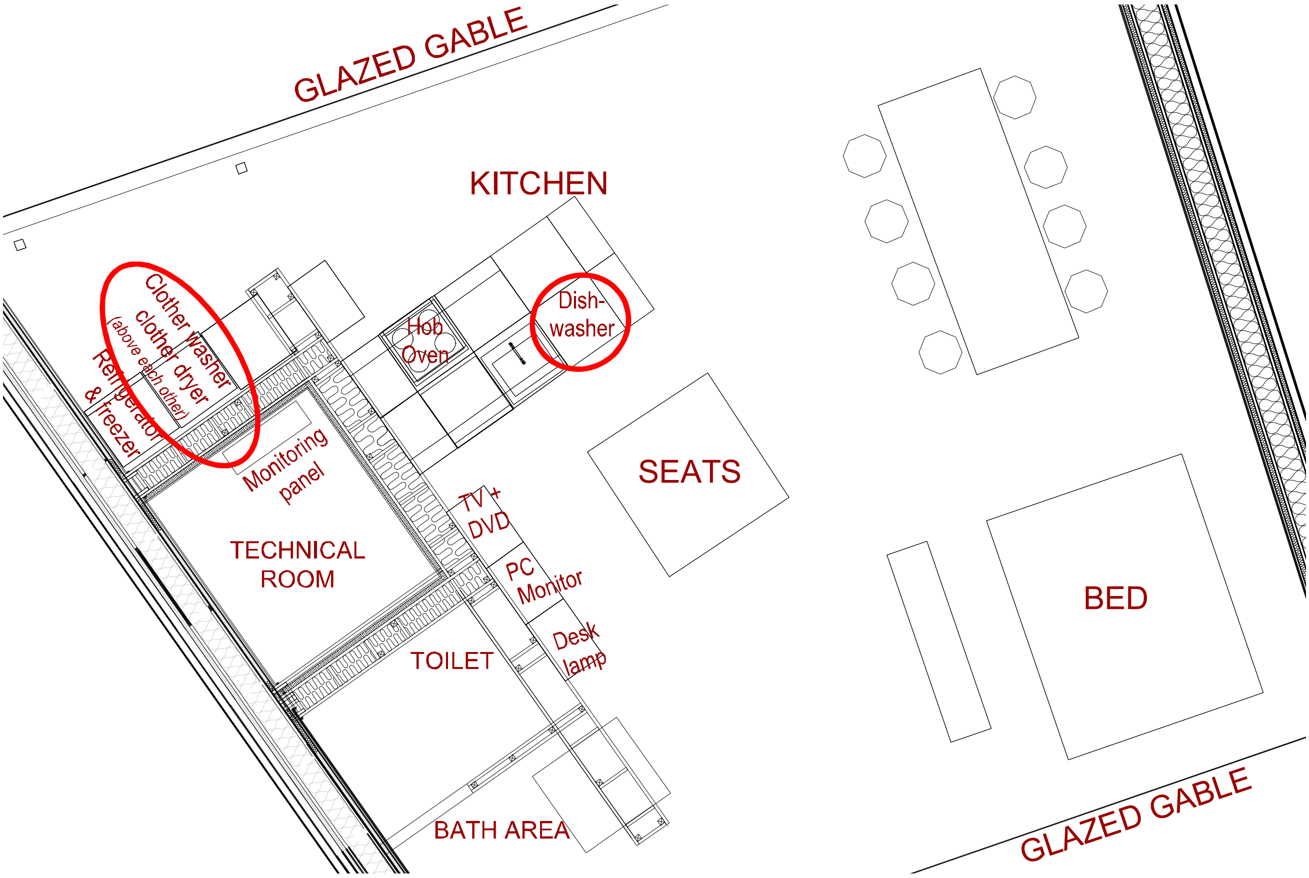


Figure 54 - Section of furniture floor plan

Clothes washer with dryer were placed separately above each other located a bit further from the dishwasher (seen on Figure 54). Exhaust pipe of the dryer was connected to the ventilation exhaust duct thus the heat could be recovered in the air-handling unit. All connections are separated from other appliances.

Figure 55 - Placement of dishwasher in the kitchen table

Each single unit is equipped with additional Asko relay board (seen on Figure 56). The relay is connected according to the factory manual to the front control panel. In a moment when the any of the 3 units needs heating water circulation the relay send a signal to the circulation pump UP20-14BX PM. The signal was not capable to run the circulation pump directly thus the relays are connected to the Schneider IHC (intelligent home control). The IHC then supply power to the circulation pump when it gets call from the relays. This solution saves electrical energy and heat losses due to zero circulation when it is not necessary.

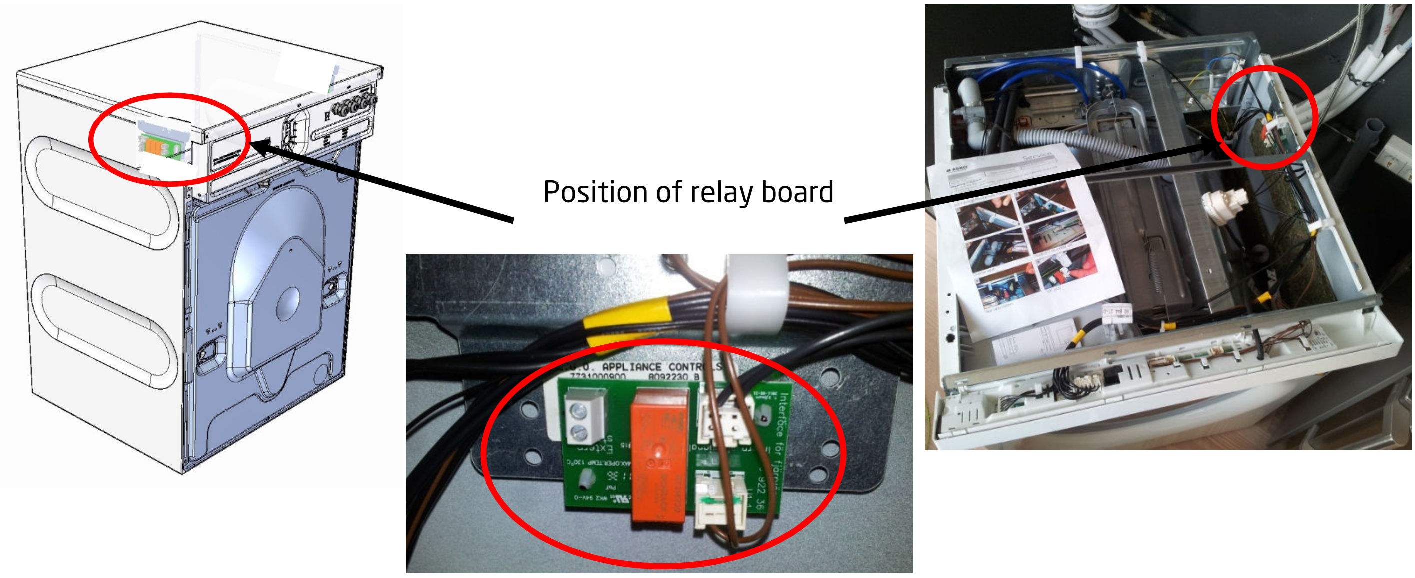


Figure 56 - Placement of relay in clothes washer

Hot water for heating the units is used directly from the hot water tank (seen on Figure 57). The risk of multiplication of Legionella is avoided by temperature set point of 60°C for the auxiliary volume of 55l. Exposure Legionella bacteria to temperature of 60°C about 90% bacteria's is killed within 2minutes. Whereas the temperature between 32 and 42 °C (that corresponds with circulation return temperature) is ideal growth range. Discharged circulation water is dumped back to the bottom of the hot water tank. It is mixed and heated to 60°C before is either tapped or used for again for the circulation. (http: //en.wikipedia.org/wiki/Legionella)

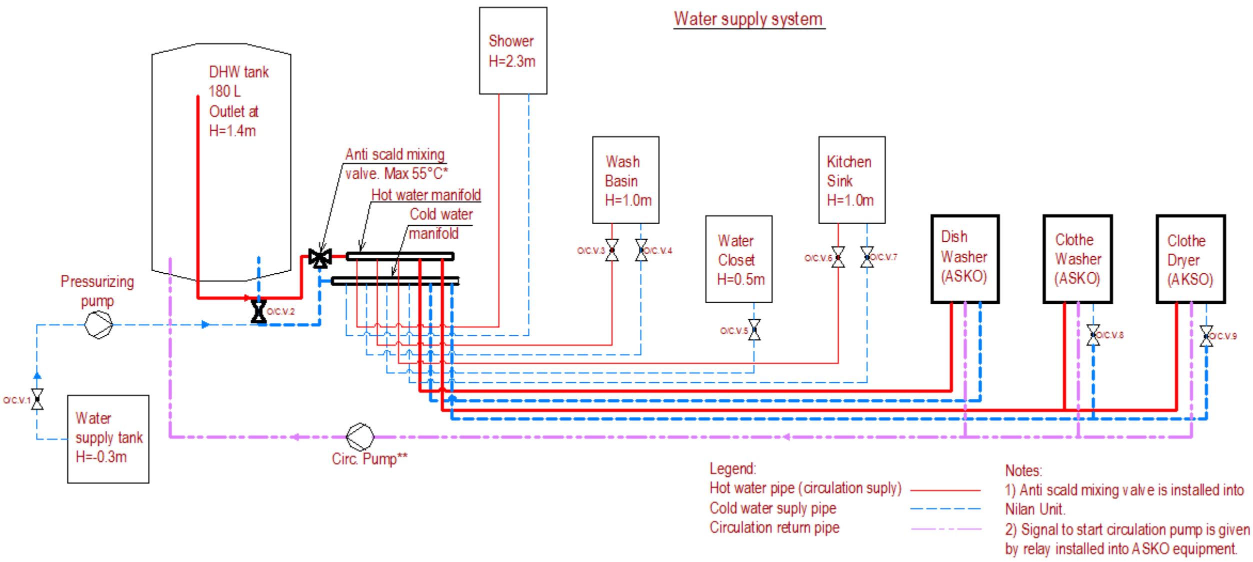


Figure 57 - Incorporation of appliances in relation to the whole house system

HWC appliances testing setup

For reasons on measurements on the HWC units and system adjustment according to the competition restrictions was build a testing setup (seen on Figure 58).

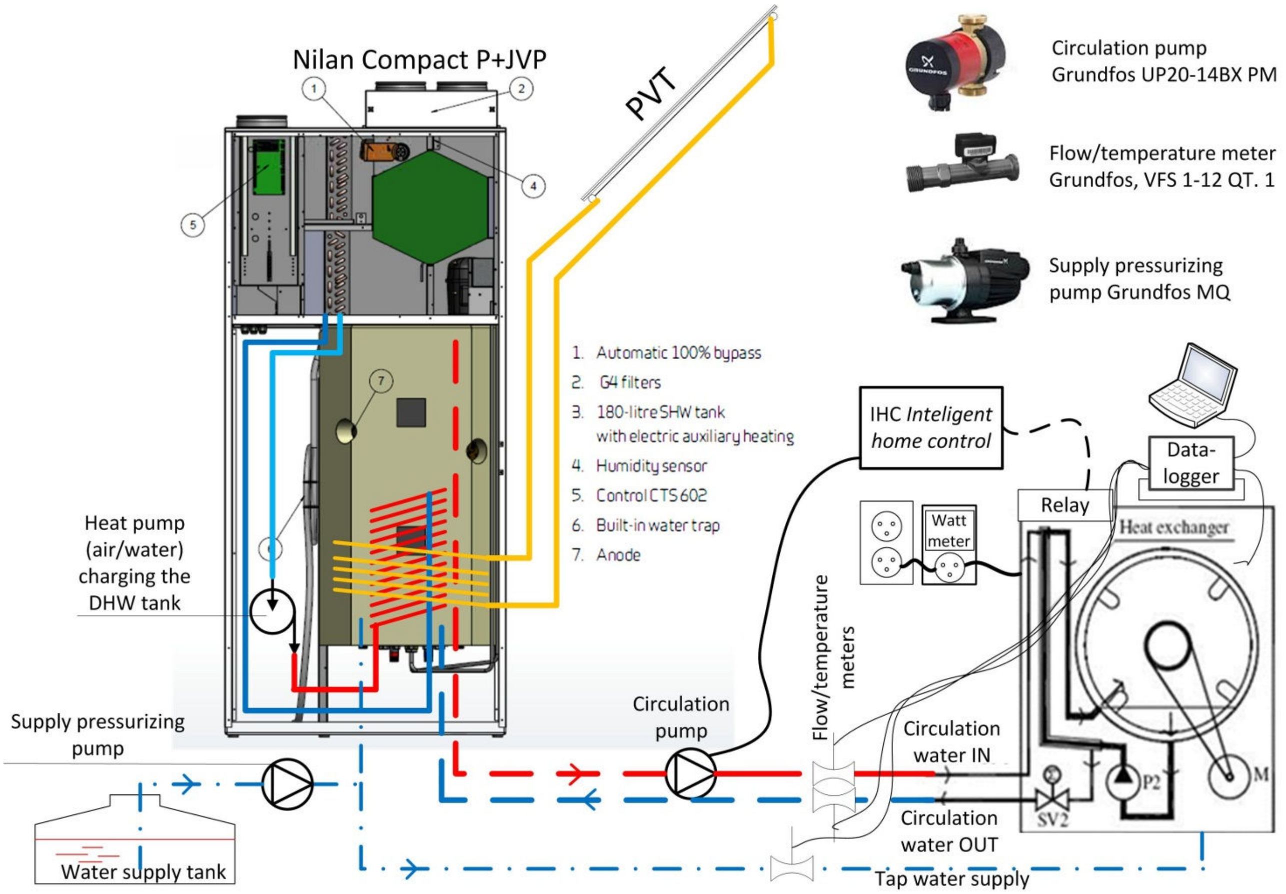


Figure 58 - Testing setup schema

The side-by-side measurements were performed for clothes washer, program 7 (Easy care) with temperature set point 40°C and spin 1200 RPM.

Pressurizing pump MQ filled the DHW tank and kept system pressurized. UP20-14BX PM when it got call from relay in the unit provided the circulation between clothes washer and DHW tank. The mass flow rate is 0.02~0.03 kg/s (1,2~1,8 l/min).

Hot water was primary produced by heat pump (air/water) via condenser placed in lower half of DHW tank. Temperature set point of DHW tank was 60°C with dead band of 5K for the auxiliary volume of 55liters. The DHW tank with total volume of 180liters is combined with air handling unit and heat pump in one unit Compact P+JVP.

Measurements were performed with 3 Flow/temperature meters, VFS 1-12 QT. 1 (See Appendix C). They have been placed on in/outlet of circulation and on supply water inlet to the unit. (seen on Figure 60). It is possible then to make a detailed energy balance and compare program even with different supply water temperatures.

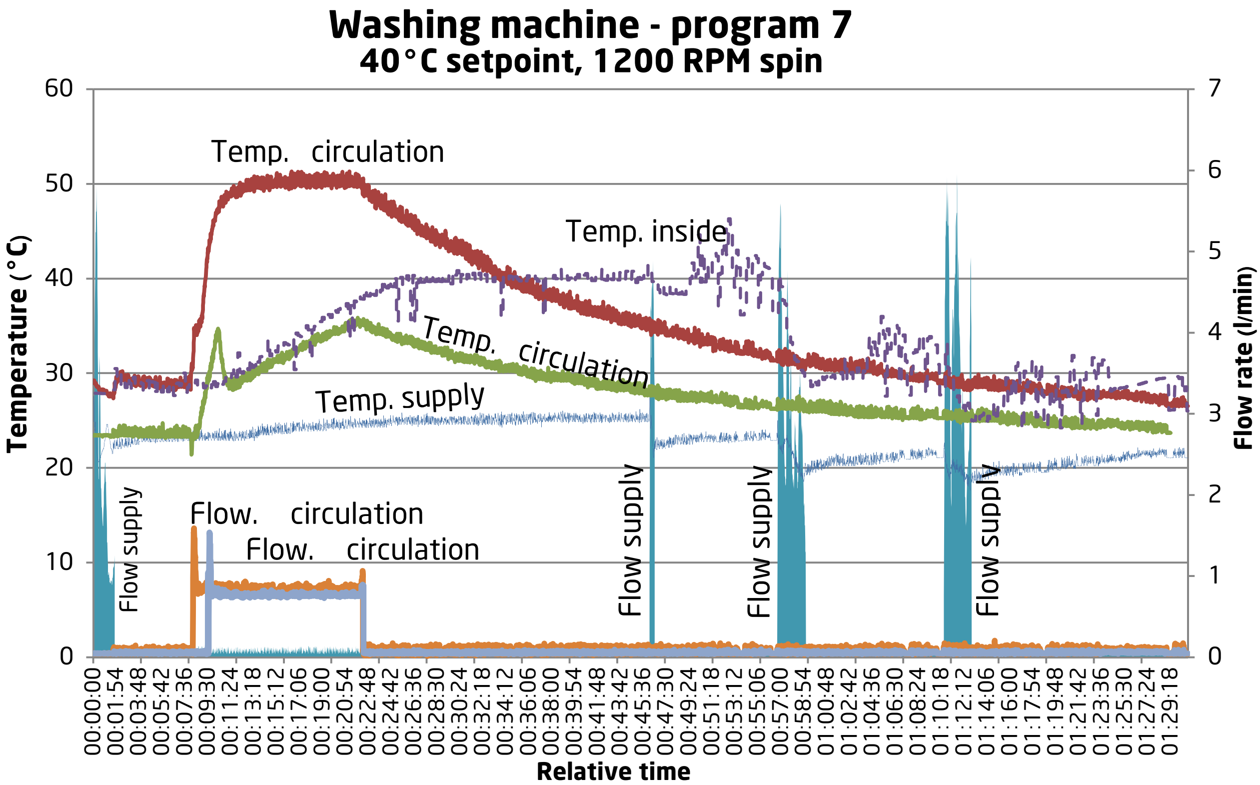
Temperature inside the machine was measured with thermocouple type K placed on the glass door. (seen on Figure 59)

Measured data were recorded on the data logger setup with Agilent system. (Seen Figure 58).

Figure 59 - Thermocouple K placemen **Figure 60 - Flow/temperature sensor placement** **Figure 61 - Logging setup**

Measurement evaluation

Data measured for the clothes washer were further investigated and evaluated. Following chart represents the aforementioned scenario.



		Electricity	Heat	
HWC	Total heat delivered by circulation water	0,075*	0,210	kWh
	Total el. energy consumed by heating element + motor	0,100		kWh
	Sum of Electrical energy and Heat for different scenarios	0,175	0,210	kWh

No HWC	Total el. energy consumed by heating element + motor	0,441		kWh

* Equivalent el. energy to reheat DHW by HP after discharge, COP= 2,80 for reheating

Chart 12 - Measurement results

The results showed that difference between uses the program with and without HWC are very significant from electrical point of view. When the clothes washer runs fully for electricity the consumption was **0,441 kWh** of electricity.

HWC mode delivered **0,210 kWh** of heat. Thus the electrical consumption dropped to **0,1 kWh** (by 80%). Equivalent el. energy for HP to reheat DHW after the circulation would be **0,075 kWh**. The heat pump works with COP of approximately 2,80 for reheating for annual average temperature in Denmark (7,4-7,7°C). If PVT would reheat the DHW tank the power consumption would be negligible. The reasons why total sum of energy for both modes is not the same might be the non-measured loses, vary or ambient temperatures or non-stable temperature of supply tap water.

The clothes washer required 4 cold water-filling in total volume of 21,5 liters. Average temperature of supply tap water was 22,8°C. This is justified by the competition requirements when the water was pumped with additional MQ pump from water tanks placed below the house.

HWC mode circulated during 14 minutes 10.9 liters of warm water from DHW tank with average temperature difference of 50,56/31,54°C. Temperature difference with maximal measured temperatures was 51.3/35.9°C.

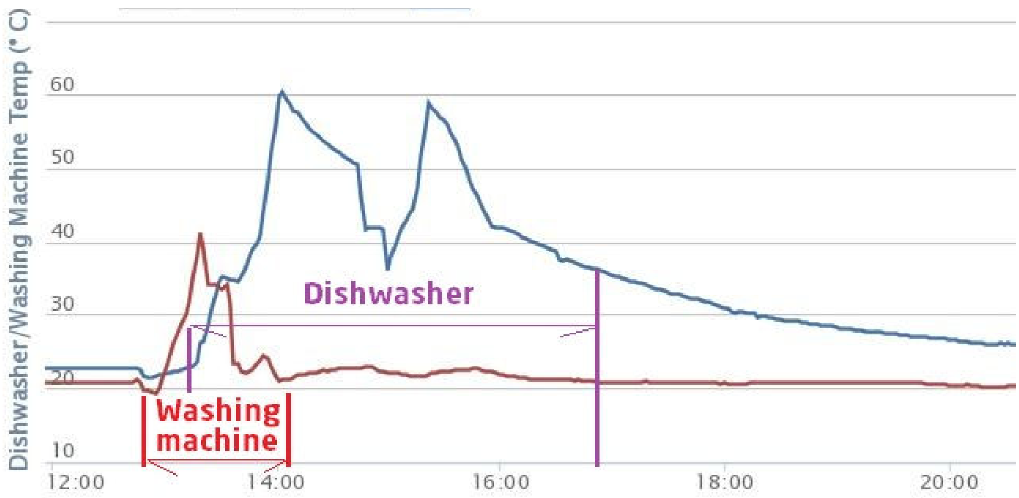


Figure 62 - Temperature measurement during the SDE competition

On the Figure 62 is seen the temperature measurement performed during the competition period in Madrid. Clothes washer ran "Timed program" number 2 for 1: 30min, 1200RPM, 50°C set point and HWC was allowed. Maximal temperature measured by SDE monitoring equipment was 41,4°C (40°C limit). Dishwasher ran the "Normal wash" program and reached 60,4°C (49°C limit).

The competition requirements were fulfilled both for clothes washer and for dishwasher.

6.4.7 Home electronics

Aim of the Home electronics sub-contest was to operate the TV, PC and home entertainment during periods indicated in competition calendar. Use of these units sub-influenced the electrical energy balance. The functionality was proved be measurement obtained from an electricity pulse watt-hour meter attached to the power circuit reserved only for these devices. Level of currently measured power should pass the 31W threshold measured previously under supervision of SDE observer just before the competition period one has begun. The meter used was the EN40P from Schneider Electric with a 10Wh resolution (see Appendix A). The accuracy of the setup allowed show only multiples of 40 W, as is seen on Figure (Home electronic measurement).

The fair value of 31W was represented by 40W in the graph and is obvious that it was one of the lowest values in entire competition !

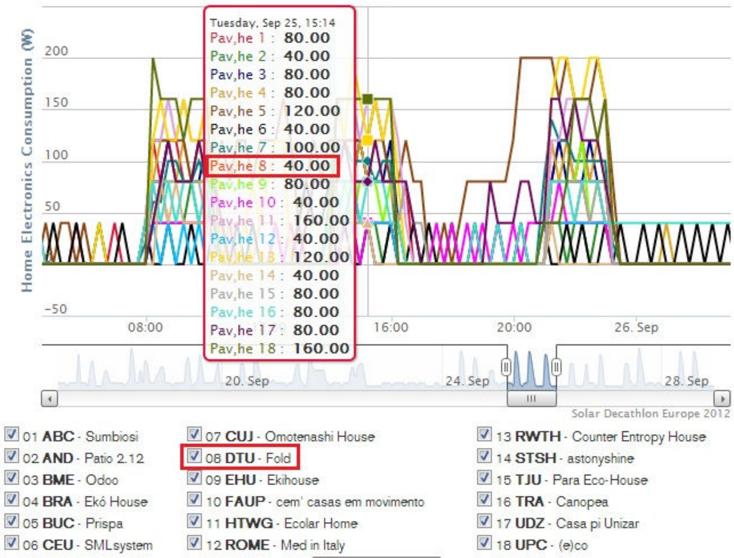


Figure 63 - Home electronic measurement

Sub-contest	Obtained points	Max. points	Clarification of the scoring
Refrigerant	4,83	5,00	Opening of the unit is doors and filling/emptying of the unit
Freezer	5,00	5,00	Doors stayed closed all the time
Clothes washer	20,00	20,00	The washing process always reached desired set point
Clothes dryer	5,30	10,00	Faculty adviser misunderstood the observer and some of the drying processes were annulated due to the drying towels on a handrail instead of missing stand dryer. Two drying processes did not reach the original weight.
Dish washer	13,12	15,00	One of the washing tasks was annulated due to abandon the site before the task was finished. Lack of or project management planning.
Oven	12,78	15,00	Slow rise in temperature.
Cooking	13,05	15,00	One task was not completely finished due to underestimate of the chosen kitchen hob power setting.
Hot water draws	17,60	20,00	2 tasks were annulated due to non-filled volume 50l. Problem was low water level in supply water tank caused by personal failure of the shift staff.
Dinner	9,67	10,00	Some of the dinner guests were not 100% satisfied.

6.4.8 Control logic strategy & Human behavior

This part was dedicated to the DTU IT team in a purpose to develop application that set out the goal to inform occupant about the energy treatment in the house and influence human behavior in purpose of improve the energy balance.

FOLD house was free of hard-wired batteries and the DHW tank was the only active storage for renewable energy in the system. As aforementioned, the heat was used with benefit in compare to use of electricity, thus the strategy for PVT is to first produce hot water with electricity (also possible to say – to cool PVT in DHW). When the there is no more need for hot water the PVT water circulation was directed to the ground where was cooled ultimately, what caused even higher efficiency of electricity production.

Energy surpluses are sold to the electrical grid. In most countries is possible to earn money this way and thus decrease the payback time of system installation. DTU system will advise the human behavior to load the generated electricity in a house when is produced, thus electricity purchase will be reduced. This supports the idea of stand-alone system. And also the price ratio is usually unprofitable in comparison between price for selling and buying from the user point of view.

The price ration is different from country to country. Thus for the control logic in the Fold house is important to ask first what are the tariffs in the country where the house is built and then decide if it worth to guide occupants to behave in relation to predicted daily profile of energy generation.

The energy loads can be distinguished into two categories:

General energy loads

> Energy needed to operate the house and the occupant cannot influence the timing. Such as ventilation, refrigerator, circulation pumps, heating the domestic water. These loads are mostly fixed except influence by the human behavior. E.g., relax the indoor climate condition to save more energy.

Task energy loads

> Energy needed to perform desired activity that can be done when any time during the day. Such as laundry, bath...

The initial idea is to guide occupants to follow the level of energy generated during the day. This means that the amount of energy generated is decreased by the General energy loads and the energy left is here to use for the Task energy loads. Those approximate energy thresholds are following:

- General energy use was determinate from energy balance and generalized to level of 1100W.
- Energy use was given for each task individually.

6.4.8.1 *Basic logic*

The intention of logic was to include energy consumption information for predefined tasks and announce to occupant when the right time occurs. What means, when the surplus of energy is big enough and stable enough according to wheatear forecast and the daytime. Info of how much can be saved if occupant will follow the guidance can be showed according to simple formula. Price for purchase of electrical energy minus price for selling times predefined amount of electrical energy for the particular task (washing clothes,...).

6.4.8.2 *Advice to use the heat and electrical tasks*

The occupant is advised to use heat (hot water, washing machine, dryer and dishwasher) always when the heat is produced. Thus, the temperature sensors T6-A, T6-B will be monitored and if any of them will reach 45 °C or more the advice will be displayed to occupant.

It is needed to behave independently with the PVT array A and B. The cell temperature can be different due to the cooling option of B part. Information about the modes is already part of the logic; sensors also register the temperature in arrays. Thermal production is threated the similar way.

The minimal irradiation threshold to advice occupant was stated according to the following table.

Table 12- Min. level of irrdiation for the General el. load

General el. load		**1100**	**W**
Cell area of the total PVT area		58	m^2
Expected consumption of HP producing the hot water		320	W
Simplified efficiency of the PVT on the el. side		15,8%	
DC/AC losses	PV losses 15% , Losses on inverter 7%	22%	
Desired net electrical yield from 1m² of roof to maintain General load		18,9	W/m^2
Minimal irradiation to maintain the general loads		93,6	W/m^2
Minimal irradiation to maintain General load +Producing the hot water		120,9	W/m^2
Minimal irradiation to reach the desired yield with safety factor of 1,3		157	W/m^2
Minimal illuminance to reach the desired yield with safety factor of 1,3		15 384	lux

For advising occupant to use the heat is the lowest irradiation 157 W/m^2 or 15384 lux. This irradiation level should provide enough energy for the general electrically load and for the heat pump in the same time. Translation between W/m^2 and lux was done according to the results of side-by-side measurement done on a site, seen Chapter 7.4.8.4.

6.4.8.3 *Weather forecast of the energy generation prediction*

The main core of this subchapter is a correlation between cloudiness and the electricity generation.

Version 1

The internet-based weather forecast gives the actual percentage of cloudiness and this value is compared with the lux level measured by lux sensor during the same time. Then the predicted cloudiness is sufficient input to predict the energy generation according the efficiency equation and the daytime intensity during the day. Scaling progress runs continually but compares only 14 days loops due to the changing the weather seasons and different sun paths during the year. By other word the system, make connection between cloudiness and expected solar irradiation during the days. This “smart” system could predict the energy production and work independently due the self-calibration.

Version 2

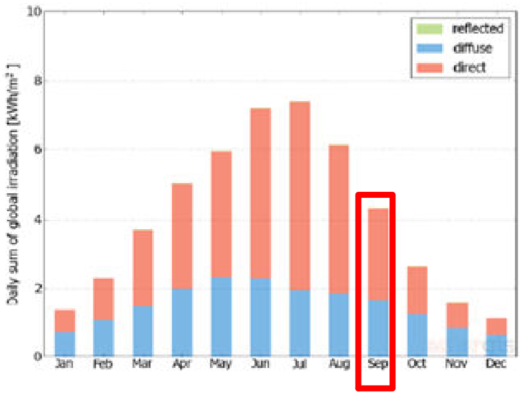
The occupant chooses the location of house in menu from list of predefined cities (Appendix *F*), or automatically via GPS. Application downloads the weather forecast with cloudiness and according to the steps, lower calculates the deduced energy available for the tasks per future day.

Deduce the daily sum of irradiation

6. Global in-plane irradiation

Fixed surface, azimuth 41° (northeast), inclination. 18°

Month	Gi_m	Gi_d	Di_d	Ri_d	Sh_{loss}
Jan	42	1.36	0.71	0.01	0.1
Feb	64	2.30	1.03	0.01	0.5
Mar	115	3.70	1.46	0.01	0.5
Apr	151	5.02	1.98	0.02	0.2
May	184	5.94	2.31	0.02	0.0
Jun	216	7.20	2.30	0.02	0.1
Jul	229	7.39	1.94	0.02	0.2
Aug	190	6.14	1.86	0.02	0.3
Sep	130	4.33	1.64	0.02	0.3
Oct	82	2.64	1.22	0.01	0.4
Nov	47	1.59	0.81	0.01	0.2
Dec	34	1.12	0.63	0.01	0.1
Year	**1484**	**4.07**	**1.49**	**0.02**	**0.2**



Long-term monthly averages:

Gi_m Monthly sum of global irradiation [kWh/m²]
Gi_d Daily sum of global irradiation [kWh/m²]
Di_d Daily sum of diffuse irradiation [kWh/m²]
Ri_d Daily sum of reflected irradiation [kWh/m²]
Sh_{loss} Losses of global irradiation by terrain shading [%]

Figure 64 - Global in-plane irradiation

For selected month linearly interpolate between the Gi_d (sum of global irradiation) and the Di_d (sum of diffuse irradiation) in same proportion as the cloudiness. See example for September bellow:

$$Daily\ sum\ of\ \ irradiation\ Gd = Did + (Gid - Did) * (1 - \%\ Cloudiness)$$

$$Daily\ sum\ of\ irradiation\ Gd = 1{,}64 + (4{,}33 - 1{,}64) * (1 - 0{,}75) = \mathbf{2,31}\ kWh/m^2$$

Take the G_d and use to state total production of entire PVT system and decrease it by the General consumption. The rest is free for the el. tasks. Show for the next day which tasks can be done.

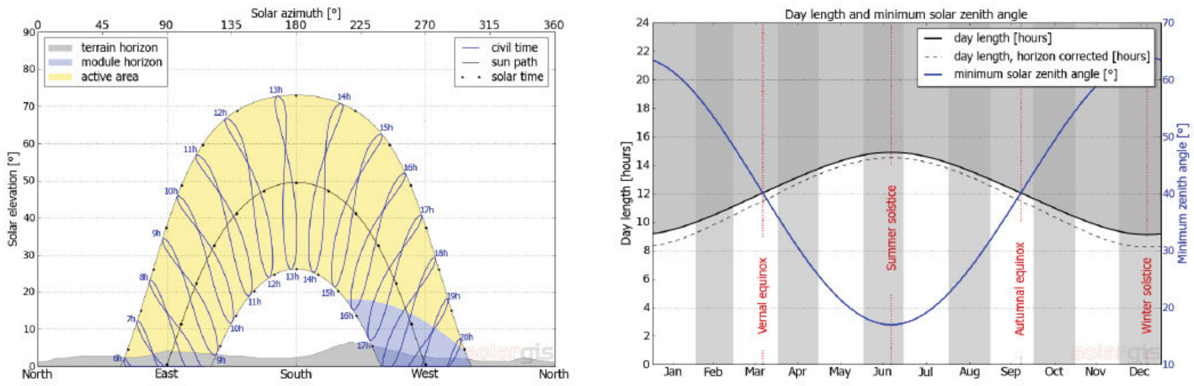
El. energy left for tasks

$$El. production\ of\ entire\ roof\ P\ roof\ = Gd * roof\ area * PV\ Efficienci * (1 - PV\ losses)$$

$$P\ roof\ = 2{,}31 * 58 * 0{,}158 * (1 - 0{,}22) = 16{,}53\ kWh\ \textit{a day}$$

$$El. energy\ left\ for\ tasks\ E\ task = P\ roof\ - General\ energy - Energy\ fro\ Heat\ pump$$

$$E\ task = 16{,}53 - 1{,}1 - 0{,}32 = \mathbf{15,75\ kWh}$$



Left: Path of the Sun over a year. Terrain horizon (drawn by grey filling) and module horizon (blue filling) may have shading effect on solar radiation. Black dots show True Solar Time. Blue labels show Local Clock Time.

Right: Change of the day length and solar zenith angle during a year. The local day length (time when the Sun is above the horizon) is shorter compared to the astronomical day length, if obstructed by higher terrain horizon.

Figure 65 - Sun path

The net energy "free" to perform the tasks should be subdivided according to the curve of the sun path along the day.

Then the system will decrease the remaining energy E task by one by one task until the rest is still positive. The tasks can go in the order seen below. Tasks that pass through will be displayed in the intension to advice occupant to plan the upcoming days.

Table 13 - Energy loads by tasks

Task	Energy load (kWh)
Clothes washing	1,20
Clothes drying	1,80
Dishwasher	1,00
Shower	1,40
Floor cleaning	0,10
Oven	0,80
Cooking on hob	0,90
Vacuum cleaner	0,60

Weather data and irradiation data were performed by *©2012 GeoModel Solar s.r.o. Report number: PV-1799-1208-3 Issued*;

6.4.8.4 *Lux and W/ m² correlation measurement*

In order to develop own control logic was needed to measure solar irradiation on FOLD house since all tests and previous calculations were based on this parameter. Fold was equipped only by lux meter, measuring the illumination, due to lower cost. Satisfactory conversion calculation was not found, therefore, was carried out the side-by-side measurement of lux meter and Pyranometer in situ in DTU campus.

Method

Data logger was synchronized with chronometer and the logging interval set to 1 minute. When the lux level has significantly changed, the value has been recorded from manual reading on the display coupled with lux meter.

Both sensors were placed next to each other and the correct angle was adjusted.

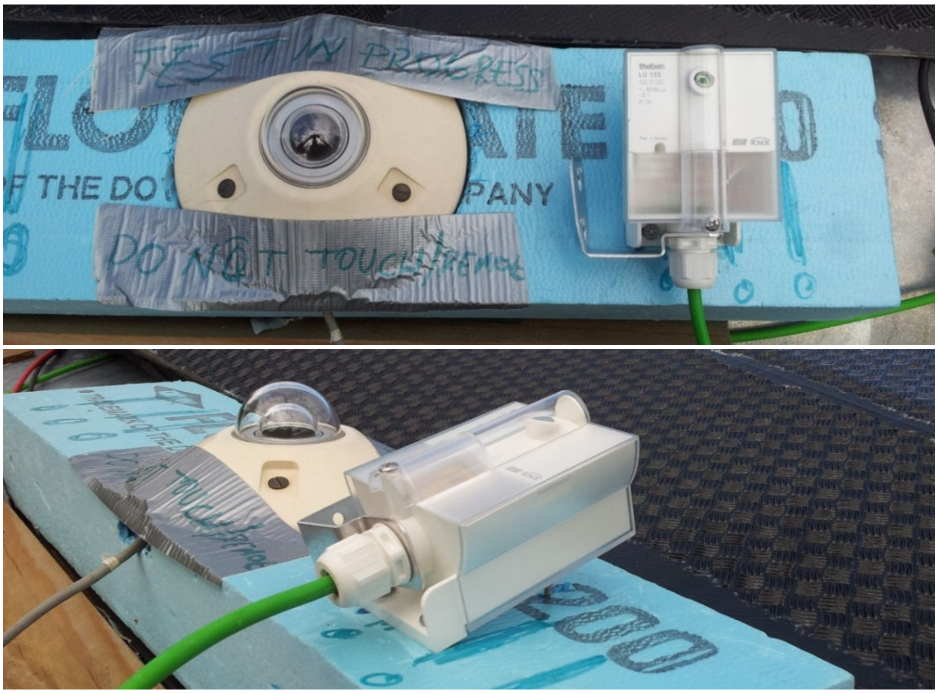


Figure 66 - Pyranometer & lux meter

Pyranometer used for outdoor test worked with a measurement error of ± 2%. The Lux sensor specifications are seen in Appendix P.

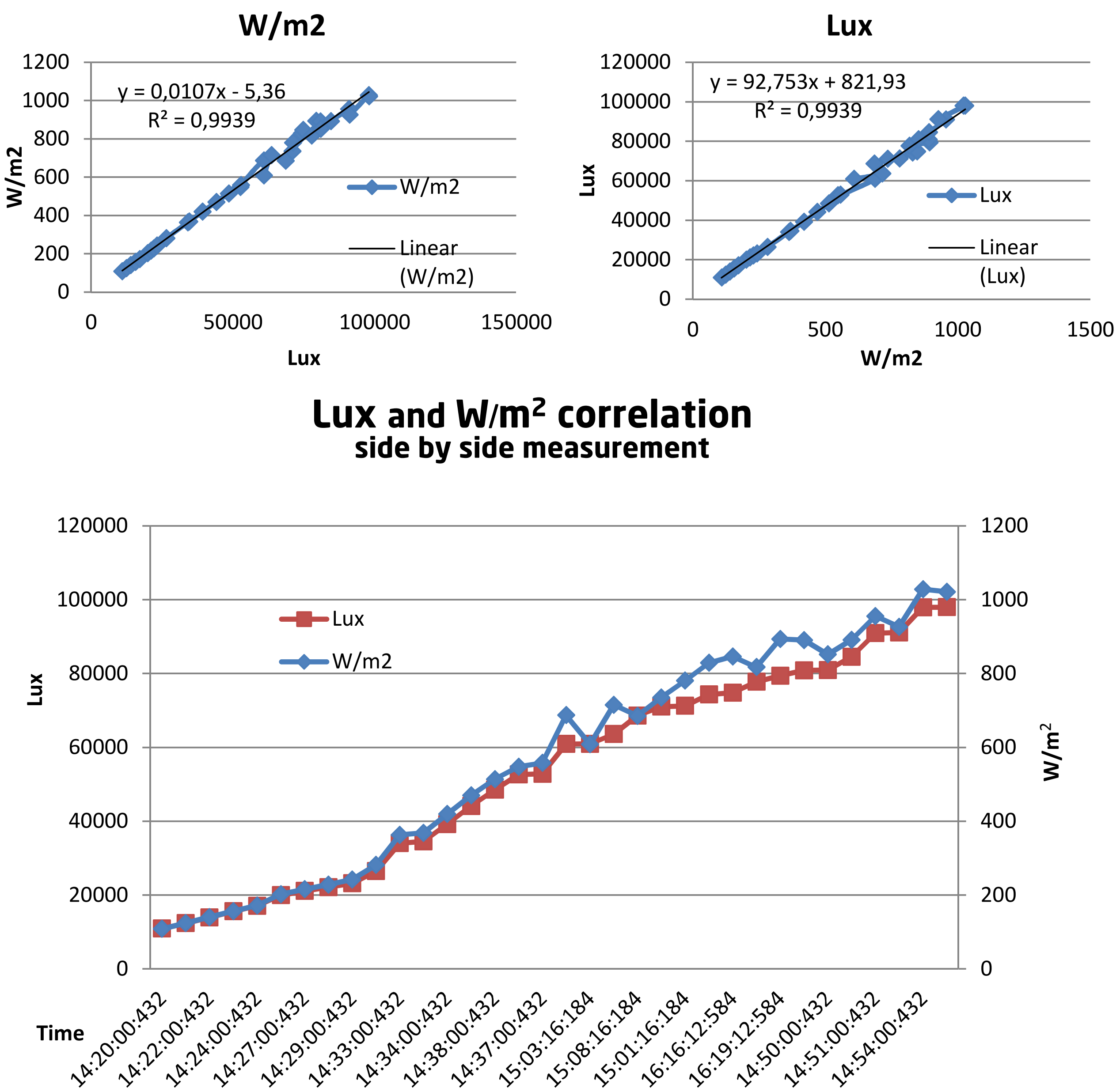


Chart 13- Lux & W/m^2 measurement

Measurements seen above were carried out for a very wide range of irradiance, from completely overcast to after azure. The obtained equations :

$$Irradiation = 0{,}0107 * lux - 5{,}36 \ (W/m^2)$$

$$illuminance = 92{,}753 * W/m^2 + 821{,}93 \ (Lux)$$

Obviously these two units are not perfectly dependent on each other because it depends on more aspects like light spectrum. This measurement fulfilled the purpose of estimation with sufficient accuracy.

6.5 Conclusion and discussion

The competition rules were deeply studied and each product was selected to fulfill the specific requirements. The price issue and foreseen use was considered as well. The complete list of appliances with technical specifications was done and negotiated with the SDE organization during several iterations. For purpose of DTU team internal use, the list was extended by "low energy guide user" for each particular type of product. Each product was also tested, optimized and the final energy consumption was noted for purpose of the Energy balance. The Appliances report is seen in Appendix A and Appendix G.

Emphasis was paid to market pre-research and contacting directly the producers. The ASKO Company was involved as an official sponsor and donated Team DTU by the innovative HWC units. Use of the HWC units in FOLD house was very first installation in Denmark.

The HWC appliances are very promising products and the measurements showed significant decrease of electrical energy load nerveless the heat would be provided by PVT or by HP in the Compact P unit. Usage of HWC in period when the PVT charge the DHW tank would cause increased efficiency of both the thermal part of PVT and thereby the photovoltaic part efficiency due to bigger temperature difference. Higher solar fraction is expected.

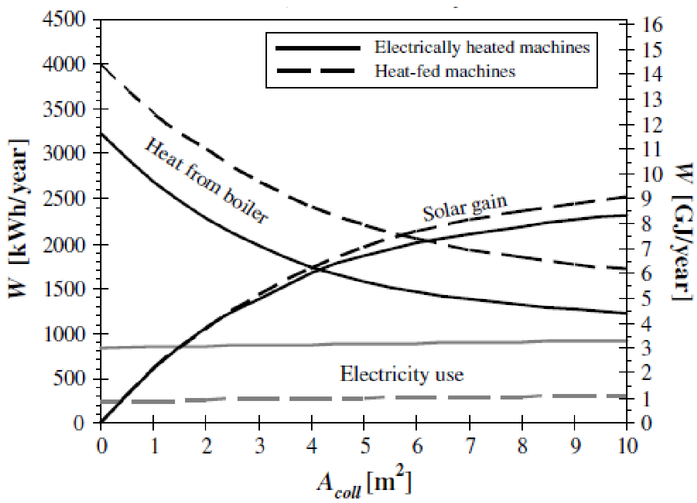


Figure 67 - Solar gain and electricity use with HWC units

Figure 68 represents similar scenario described as: "Simulated solar gain, electricity use and heat from boiler *W* as a function of collector area *Acoll* for the SDHW-system in Stockholm with HWC heat-fed machines (dashed lines), and electrically heated machines (continuous lines), respectively. The electricity use includes electricity to all circulation pumps in the system and to the dishwasher and the washing machine." (*T. Persson, Mats Ronnelid, 2006*)

HWC units were fully integrated into FOLD house. Individual improvements were done by the circulation loop common for all 3 appliances. Air exhaust from tumble dryer was coupled with ventilation system that recovers the waste heat during cooling season and supplies the same amount of fresh air in a room in the same time.

The washing cycle showed 4 fresh water fillings but only after the first one the HWC was utilized. Critical evaluation of the measurement results could call to question about lower delivered temperature to the machine than originally calculated. The expected temperature on the boundary of clothes washer was 55°C but only 50,56°C. The temperature drop might be caused by lack of insulation work spend in the piping by responsible subjects.

The doubt also evocated the use of the supply water tank that caused higher supply water temperature then would be from the common water grid.

Asko is a pioneer of the HWC technology and even the first generation is a great success there is a room for improvements. The time for recirculation and transmission of heat for HWC mode is significantly longer than for the standard mode. This is caused by lower efficiency of the water to water (water to air) heat exchanger inside the units in compare to the efficiency of the direct electrical heating elements that are conventional. Solution can be a new combined unit that would marge the ECO and HWC lines in one. One more inlet for hot water would allow the unit to mix the right filling temperature instead of taping just the cold water. The very first "heated water circulation" would be minimalized just to recover the heat loss caused by thermal mass of material inside the unit that has an ambient temperature (dishes, clothes). The program period would be shortened and the HWC mode would be more attractive for the user.

The solution where would be directly connected HP to the HWC loop was considered (see Appendix A). But it was proved by calculation that the inbuilt HP in Compact P unit is not powerful enough to produce temperature width enough for the design flow rate in HWC loop.

The solution would be to change logic of the HWC appliances when would be allowed to run HWC with lower supply temperature and circulate longer. Another option is to decrease the flow rate for circulation thus the inlet temperature would rise up.

The IT team DTU created an informative application for occupant as an extra service. This application realized on tablet can control electrical based systems like lights, sockets, window opening, indoor climate set points and also it gives to the user the overview of actual energy balance with possibility to track energy balance history and prediction. Another function is the displayed weather forecast for a week in advance and actual thermal condition inside and outside the house. Finally yet importantly is the occupant advice how to behave to decrease the energy loads and how to utilize the on-site generated energy most efficient way. Content of the application is also based on the logic described in Chapter 7.5.

Figure 68 - Print screen of application used in FOLD house

7. Energy balance process and results

Electrical energy production is based on 67,8m^2 PVT (photovoltaic thermal) installed on tilted roof. The heat extracted from PVT panels is transferred to DHW tank or to the borehole. Depends on what decides the control logic is most beneficial in a particular moment.
This way is the active roof area more effectively utilized regardless the PVT modules are used as final roof envelope that replace conventional cladding or tiles.

7.1 List of electricity loads

Please see spread sheet including detailed description of every single electricity load in W in one hour step thus the power consumption in Wh is clearly visible, Appendix T (just example, full only digitally).

7.2 Description of the tools

Electrical energy balance has been performed by software TRNSYS using the weather data file SWEC (Spanish Weather for Energy Calculations).
Computation model of Entire house system was created in TRNSYS. Output file with time step of 6min was simplified to one-hour average step and transported to a spreadsheet. Energy loads for competition week were simply included in the spreadsheet, since no dynamical behavior is expected.
So the generated energy and HVAC energy needs were dynamically simulated in software TRNSYS. The energy loads were included manually in spreadsheet. Energy balance was created very clearly way, which is easy to follow and control in the spreadsheet. (see Appendix A, R) Presented is only an example, full version is available only in digital form.

7.3 Results of the simulations

Electricity Energy Balance is seen in 3 attached spread sheet files: Energy balance with Chiller.xlsx, Energy balance without Chiller.xlsx, Energy balance annual.xlsx. The overall Competition period, Monthly and Annual results are showed lower in this report.

Because of lack of communication between organization and Team DTU occurred a situation when Team DTU was informed that the electrical loads for running the chiller, replacing the borehole, is taken into the electrical energy balance. Even previous communication statement claimed an offset of the measured loads by chiller.

Please see below the comparison of simulated electrical energy balance for Competition period with original solution "Without Chiller" and incurred situation "With Chiller".

7.4 Scenario with chiller

On the chart below is seen the El. balance during the Competition period with consideration of el. loads for external chiller that simulates the borehole. The steep peaks represent brunt of solar production in daily time. Since the Fold house do not have el. energy storage the surplus is send to the el. grid. The energy injected to the grid make an offset of the highest peaks. El. loads create the mutual difference. When the el. production by PVT is not sufficient to charge the house, electricity is extracted from the el. grid. That mainly happens during evenings, nights and mornings.

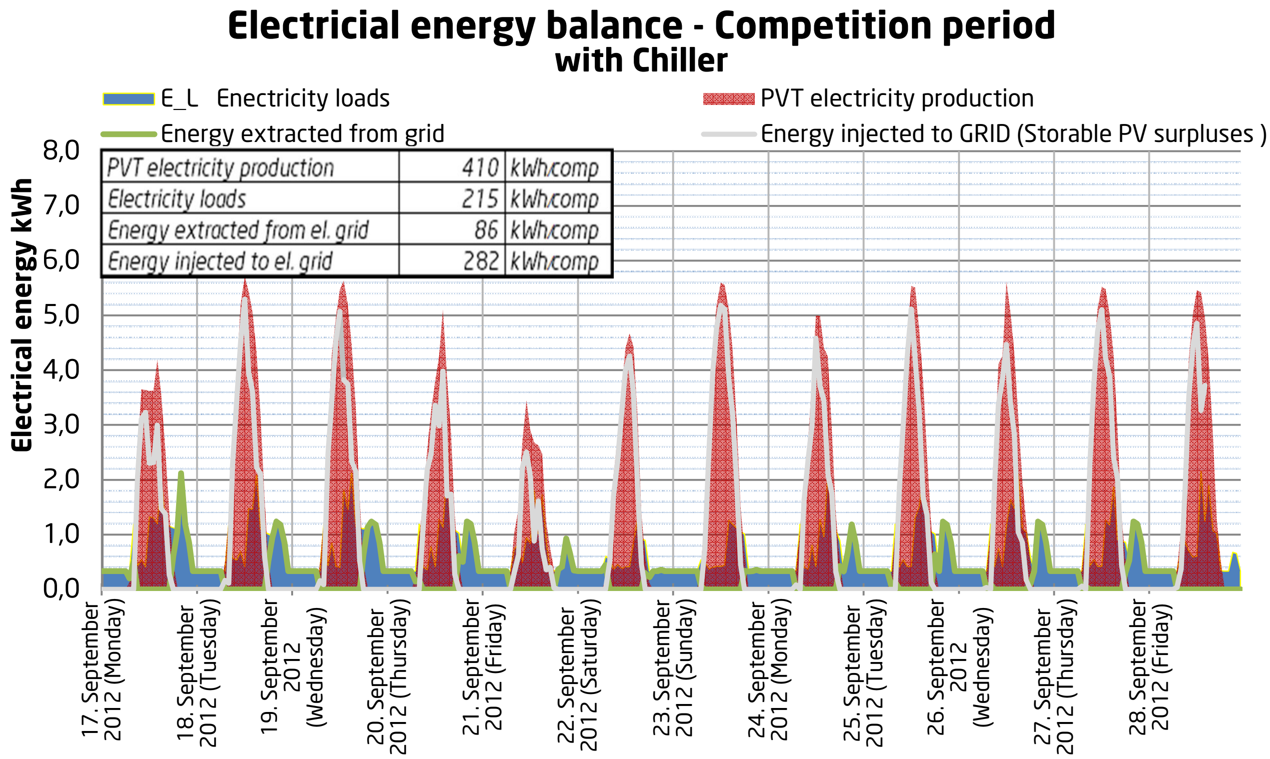


Chart 14 - El. energy balance for Comptition period with chiller

As is seen on the chart above the maximal simulated electricity production raised up to 5,711 kW and the electrical energy balance ended with energy surplus almost twice big as electricity load for the competition period.
About 40% of the electrical loads supposed to be covered by the electrical grid thus 60% of electricity used was expected to be loaded during the productive period without overlapping the production level.

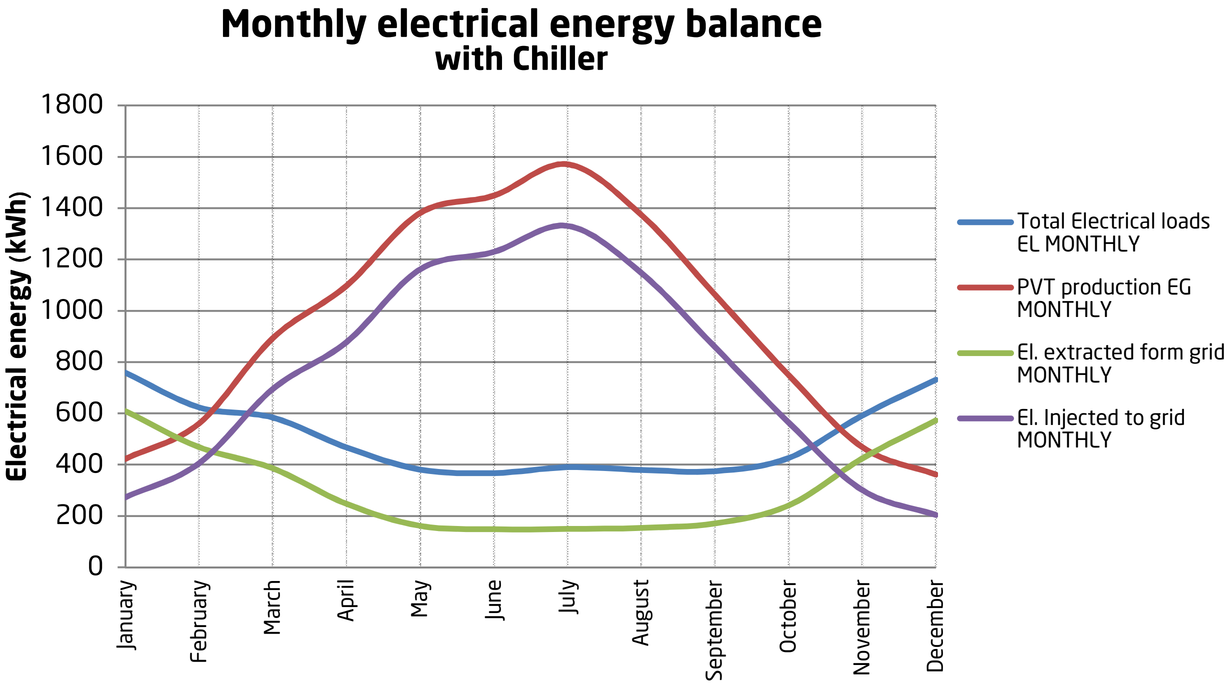
In the tables below is seen expected performance and point yield according to the competition rules introduced in chapter 4.1.1.. Results are based on dynamic simulation of energy production and loads within the competition period 17^{th} – 28^{th} of September 2012. This scenario is conditionally to weather data file SWEC (Spanish Weather for Energy Calculations) and location Madrid - Spain.

Table 14 - The expected achieved results (with chiller)

Sub. Contest 4.1 Electricity autonomy		
Total el. generation	*410*	*kWh/ competition period*
Total el. load	*215*	*kWh/ competition period*
Electricity Autonomy	*195*	*kWh/ competition period*
Percentage per scored period	*100*	*%*
Points earned	*50*	*of max 50 points*

Sub. Contest 4.2 Temporary Generation-Competition period			
EG_L en. generated and loaded in a same time		*69*	*kWh/ competition period*
EL energy loaded in a scored period		*215*	*kWh/ competition period*
	Correlation ξ	*0,32*	*-*
Points obtained	*13*		*of max 40 points*

Sub. Contest 4.3 Load Consumption per Measurable area		
Load consumption per m. area E_{ls}	3,25	*kWh/ m2 * comp. period*
Measurable area of the house	66,2	*m2*

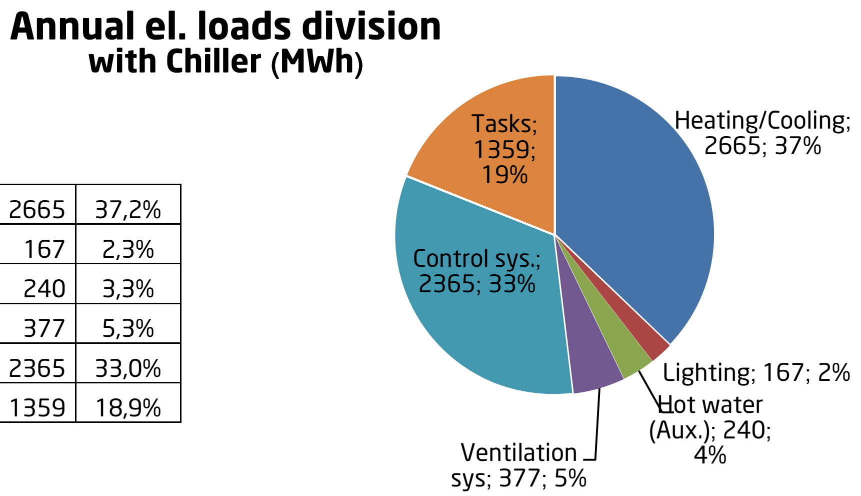


All values in kWh	**Total Electrical loads E_L MONTHLY**	**PVT production E_G MONTHLY**	**El. Extracted form grid MONTHLY**	**El. Injected to grid MONTHLY**	
January	1001	423	848	269	kWh
February	809	561	650	401	kWh
March	731	893	523	685	kWh
April	549	1097	314	861	kWh
May	387	1381	163	1156	kWh
June	366	1449	148	1230	kWh
July	384	1571	148	1336	
August	374	1374	152	1153	kWh
September	414	1063	178	827	kWh
October	459	750	267	558	kWh
November	738	469	561	292	kWh
December	961	362	797	198	kWh
Annual	**7173**	**11391**	**4749**	**8967**	**kWh**

Chart 15 - Monthly el. energy balance with Chiller

Chart above showed expected monthly division of energy balance over the typical year in Madrid.

Heating/ Cooling	2665	37,2%
Lighting	167	2,3%
Hot water (Aux.)	240	3,3%
Ventilation sys	377	5,3%
Control sys.	2365	33,0%
Tasks	1359	18,9%



PVT total el. generation	***11391***	***kWh/ year***
	224	*kWh/ m² PVT cells* year*
Total el. load	*7173*	*kWh/ year*
	108	*kWh/ (year * m² floor)*
Electricity Autonomy	*4218*	*kWh/ year*
(Overall energy surplus)	*64*	*kWh/ (year * m² floor)*
	1,6	*Times more el. en. generated than used*
Total el. energy extracted from el. grid	*4749*	*kWh/ year*
Total el. energy injected to el. grid	*8967*	*kWh/ year*
PVT heat production	*85*	*kWh/ year*
Floor area	*66,20*	*m²*
PVT cell area	*50,81*	*m²*

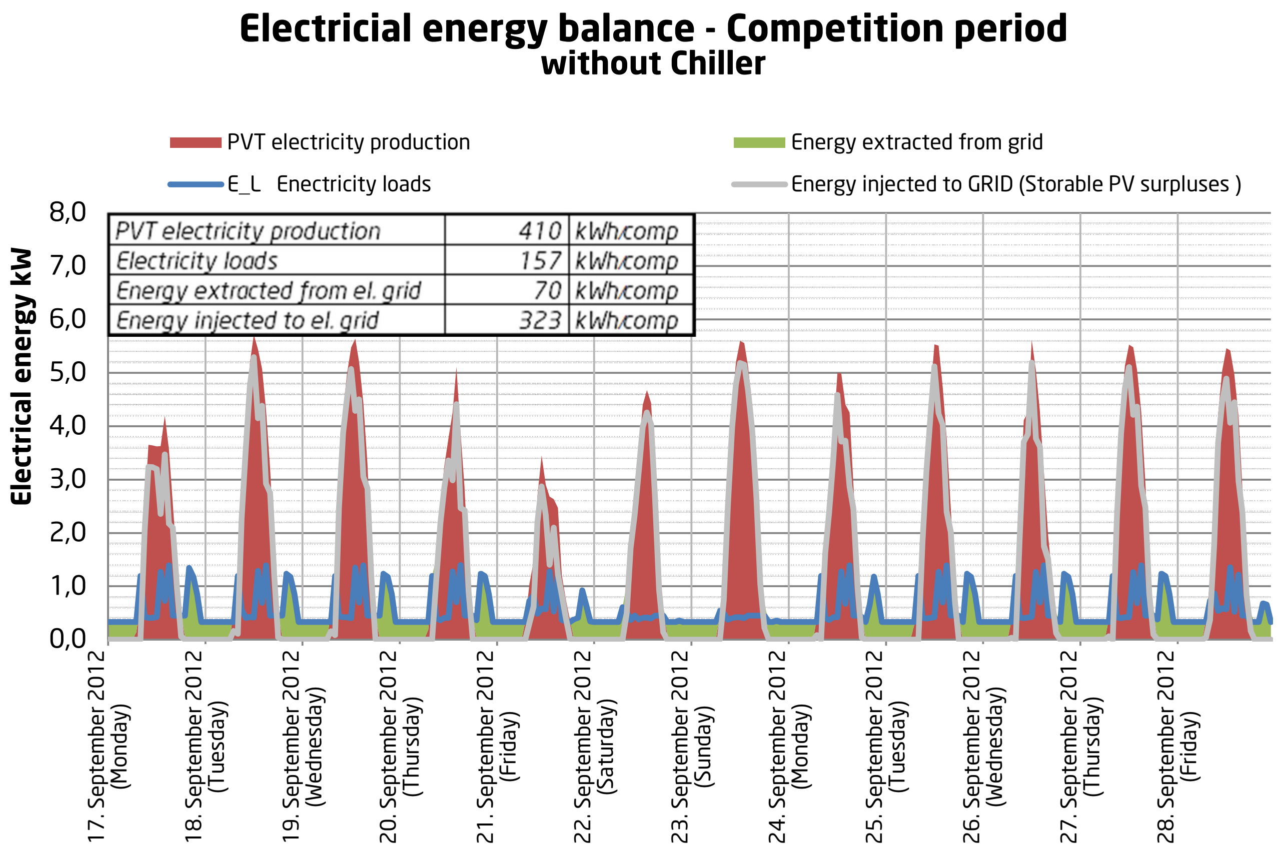
Chart 16 - Overall Annual el. energy balance for scenario with chiller

7.5 Scenario without chiller

On the chart below is seen the El. balance during the Competition period when the loads for external chiller are neglected. Comparison with the previous situation shows that the el. loads are 26% lower for Competition period and 15% annually. Thus the steep peaks that represent brunt of solar production are even more significant. Energy injected to the grid is higher by 14% for Competition period and 1% annually. This is probably caused by different behavior during non-cooling season.

The el. energy extracted from grid is lower either, 13% for Competition period and 21% annually. The el. loads same as the el. generation can deviate from simulated values due to different weather conditions according to the average values in weather date file. In a case of adverse weather the increased level of electrical load is expected as a consequence of poor heat production by PVT. Thus, the heat is generated by el. heat pump.

It is expected to load more energy due to lower efficiency of HVAC systems compare to simulated setup and due to conditions, that does not match idealized situation.



As is seen on the chart above the electricity production is obviously identical to the previous setup-The electrical energy balance ended with energy surplus 2,6 times bigger than the electricity load for the competition period.

About 44% of the electrical loads supposed to be covered by the electrical. This value relatively rose according to previous scenario because of lowered loads of chiller in the productive period.

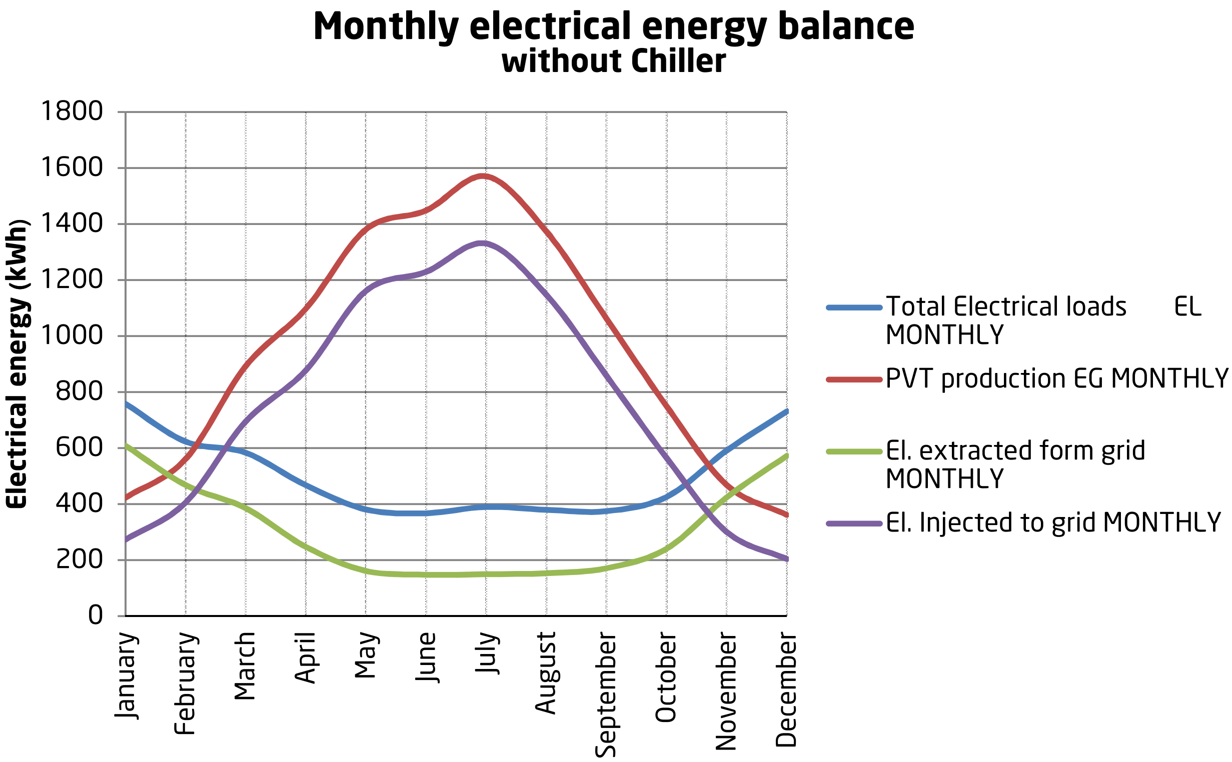
Table 15 - The expected achieved results (without chiller)

Sub. Contest 4.1 Electricity autonomy		
Total el. generation	*410*	*kWh/ competition week*
Total el. load	*157*	*kWh/ competition week*
Electricity Autonomy	*253*	*kWh/ competition week*
Percentage per scored period	*100*	*%*
Points earned	*50*	*of max 50 points*

Sub. Contest 4.2 Temporary Generation-Consumption Correlation		
E_{G_L} *en. generated and loaded in a same time*	*46*	*kWh*
E_L *energy loaded in a scored period*	*46*	*kWh*
Correlation ξ	*1*	*-*
Points obtained	*40*	*of max 40 points*

Sub. Contest 4.3 Load consumption per measurable area:		
Load consumption per m. area El_s	2,29	*kWh/m2*
Measurable area of the house	66,2	*m2*

The monthly el. Energy balance shows that highest energy need is used for space heating during the winter period. The extracted energy from grid follows the electrical loads when the PVT production is not high enough.

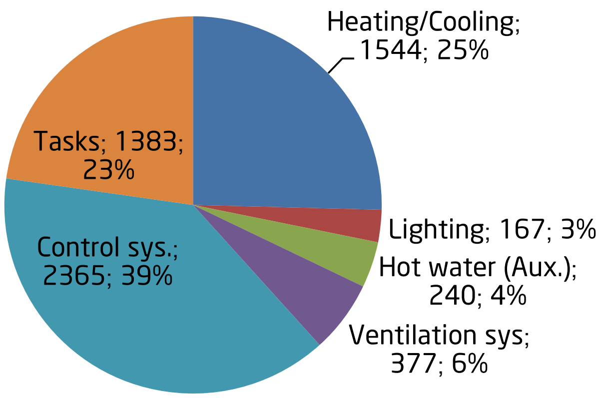


All values in kWh	Total Electrical loads EL MONTHLY	PVT production EG MONTHLY	El. extracted form grid MONTHLY	El. Injected to grid MONTHLY	
January	759	423	609	273	kWh
February	623	561	468	405	kWh
March	584	893	386	695	kWh
April	467	1097	248	877	kWh
May	381	1381	161	1161	kWh
June	367	1449	148	1229	kWh
July	390	1571	150	1331	kWh
August	380	1374	153	1148	kWh
September	375	1063	171	859	kWh
October	426	750	241	565	kWh
November	592	469	424	301	kWh
December	731	362	573	204	kWh
Annual	**6076**	**11390**	**3733**	**9048**	**kWh**

Chart 17 - Monthly el. energy balance without Chiller

Annual el. loads division
without Chiller (MWh)

Heating/ Cooling	1544	25,4%
Lighting	167	2,8%
Hot water (Aux.)	240	3,9%
Ventilation sys	377	6,2%
Control sys.	2365	38,9%
Tasks	1383	22,8%



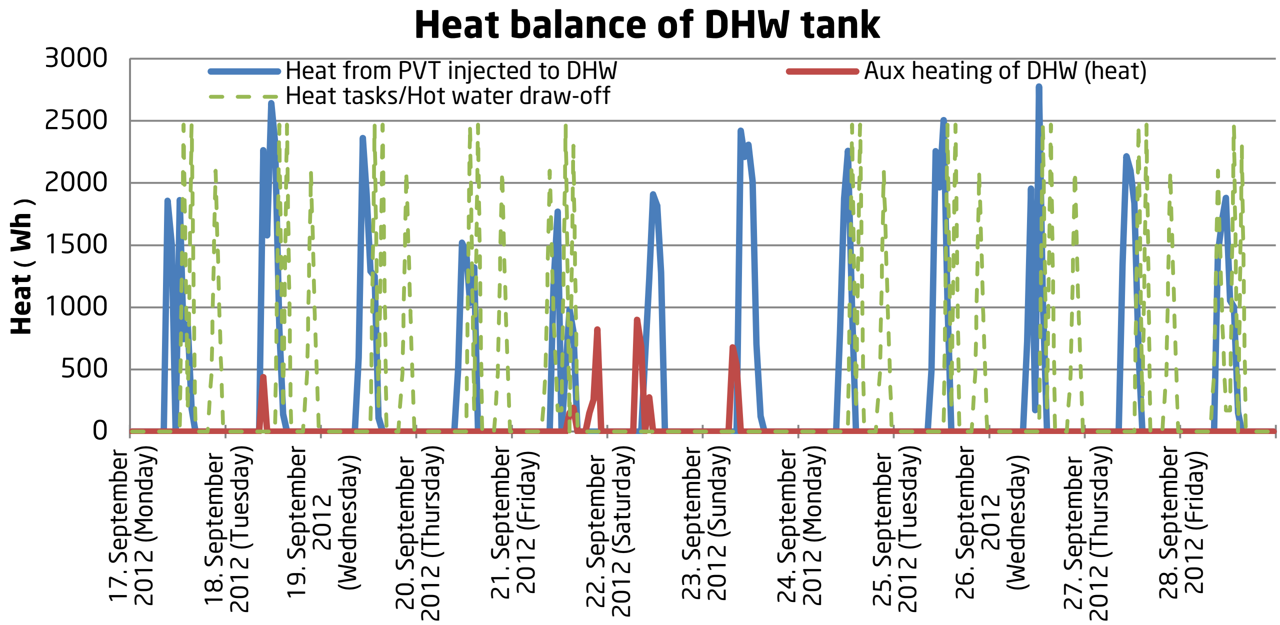
Total el. generation	***11390***	***kWh/ year***
	224,17	*kWh/ m^{2}PVT cell* year*
Total el. load	*6075,8*	*kWh/ year*
	91,78	*kWh/ (year * m^{2}floor)*
Electricity Autonomy	*5314,4*	*kWh/ year*
(Overall energy surplus)	*80,279*	*kWh/ (year * m^{2}floor)*
	1,9	*Times more el. en. generated than used*
Total el. energy extracted from el. grid	*3733*	*kWh/ year*
Total el. energy injected to el. grid	*9048*	*kWh/ year*
PVT heat production	*1933,9*	*kWh/ year*
Floor area	*66,20*	*m^2*
PVT cell area	*50,81*	*m^2*

Chart 18 - Overall Annual el. energy balance for scenario without chiller

The overall annual electrical energy balance simulated for typical conditions in Madrid ended with surplus of 5314 kWh; 1,9 time relatively more than used. The maximal electricity production occurred in July when was supposed to be reached limit of 7,127 kW.

7.6 Heat balance

Simulation data were analyzed and the folowing heat balance was made.



Heat consumption for tasks and Hot water draw-off	*86,150*	*kWh/comp*
Heat generated in PVT and injected to DHW	*88,181*	*kWh/comp*
Aux heating of DHW (heat maintained by heat pump air to water)	*5,069*	*kWh/comp*
Correlation between heat from PVT/ aux heating	*17,4 / 1*	-
Correlation between electricity used to run PVT circ. pump/ aux heating	*1,7 / 1*	-

Chart 19- Heat balance during the Competition period

During the competition period in Madrid was supposed to be delivered 88,18 kWh of heat to the DHW tank, 5,07 kWh supposed to deliver auxiliary heating. During the tasks was draws 86,15 kWh. The difference between heat delivered and taped was the heat loss of DHW tank.
As is seen on figure above, during weekend were no tasks performed and the tank was getting charged. It is approximately 9,4 kWh of heat to fully charge the tank. Solar fraction was supposed to be 89% thus almost all heat was delivered by the PVT.

Table 16 - Annual heat balance

Total Heat into DHW tank contributed by PVT	*1831,0 kWh*
DHW tank, aux heat consumption	*795,2 kWh*
DHW tank, heat loss	*339,3 kWh*
Pump A on DHW	*717,2 h*
Pump B on DHW	*717,2 h*
Pump B on PV/T cool	*388,9 h*
Pump B on total	*1106,1 h*
NUSE (Net Utilized Solar Energy) [2]	*1338,2 kWh*
NUSE/m² of PV/T area	*19,7 kWh/m²*
Solar Fraction [3]	*62,70%*

[2] NUSE is the heat drew from the tank and heat losses decreased by heat produced by auxiliary heating.

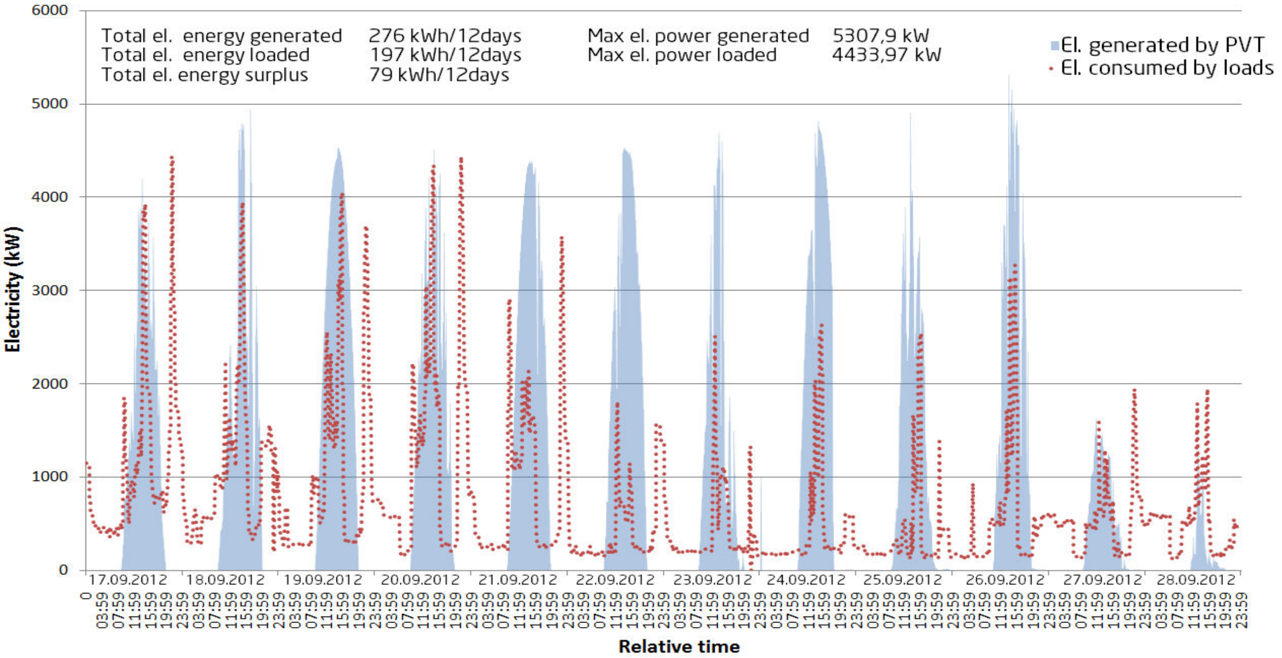
[3] Solar fraction is the amount of energy provided by the solar technology (NUSE) divided by the total energy required.

For the location of Madrid the thermal part of PVT was supposed to provide 62,7% of all required heat to the DHW tank within the typical year.

7.7 Energy balance measured during the competition period

The detailed comparison between simulated outcome and real measurement during the competition period was not possible due to the logistic issue. Even all measurable variables were logged the data were not provided by programmer team on time. Analysis of these data is probably considered in phase of research for SDE 2014.

At least the overall comparison was based on energy balance metadata documented on SDE websites.



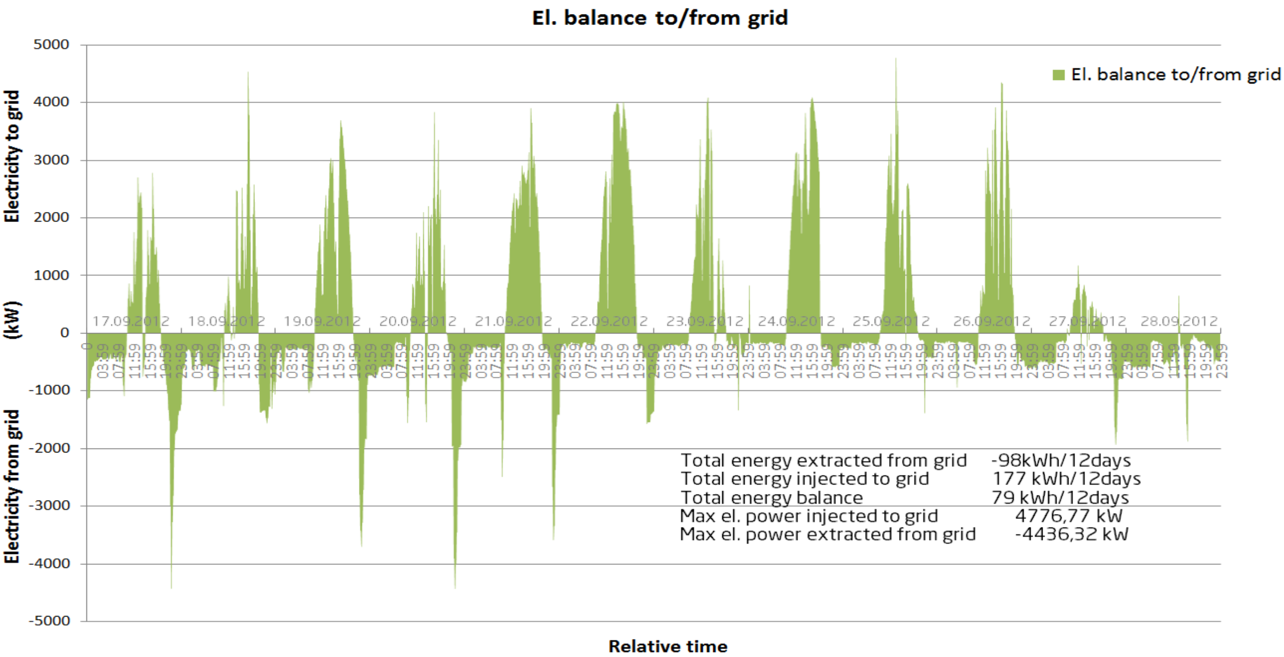


Figure 69 - Enectrical energy balance measured

On the two figures above is seen the performance of FOLD house in the real conditions during the competition. The peak production of PVT system reached 5,308 kW instead of 5711 kW, thus 7% less than was expected. The total energy production over the competition period was 32,7% lower. Reason for worse performance might be:

- Rainy weather last two days of the competition. That weather vary from the data files
- Demaged cells decreased the overall PV efficiency
- Dirtiness of the PVT surface. The glass was cleaned 25th of September

On the other side the electrical loads were lower by 8,4% according to the simulated results. There are two reasons:

- The energy consumption was artifically overestimated because of the safety factor
- During the competition period was continesly adjusted and improved the use of applainces and the electrical loads of control systems were cut down where possible.

Energy injected to the grid dropped to about 40% due to the worse electricity production.

The Electrical energy balance is showed on Figure 70. Line dedicated to the FOLD is highlighted and its length signs the number of points obtained. The scoring was based on the concept introduced earlier in this report:

Electricity Autonomy obtained full point's as was calculated, thus electrical energy balance ended positive with more than10 kWh surplus, when only energy generated between 10-17h was taken into account.

Temporary correlation turned out to be better than was expected. Expected was correlation about 32% (13p) and the result was 54% (21,77p). The reasons are two. Firstly, the use of chiller was manually controlled and run as much as possible during the period when is energy produced. Secondly, SDE made a change just one day before the competition and the trunked period was extended by one extra hour. Thus it was little easier to fit in to the range.

Electrical use per measurable area well corresponded to the expected value. The organization measured 3,04 kWh/m^2 $_{\text{competition period}}$ and expected was 3,25 kWh/m^2 $_{\text{competition period}}$; 6,5% variation.

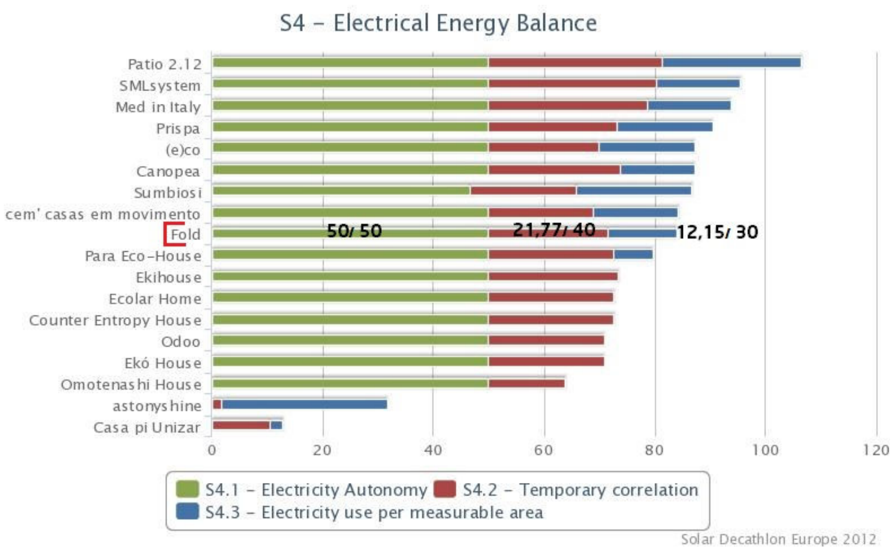


Figure 70 - El. Energy Balance including the extra loads by chiller

Comparison of measurement results and Energy balance model showed significant similarity even the conditions were changed and second scenario was created. If the electrical loads for chiller, as was planned, would not be included in to the balance FOLD would probably win this contest because in the first scenario was expected gain of full points.

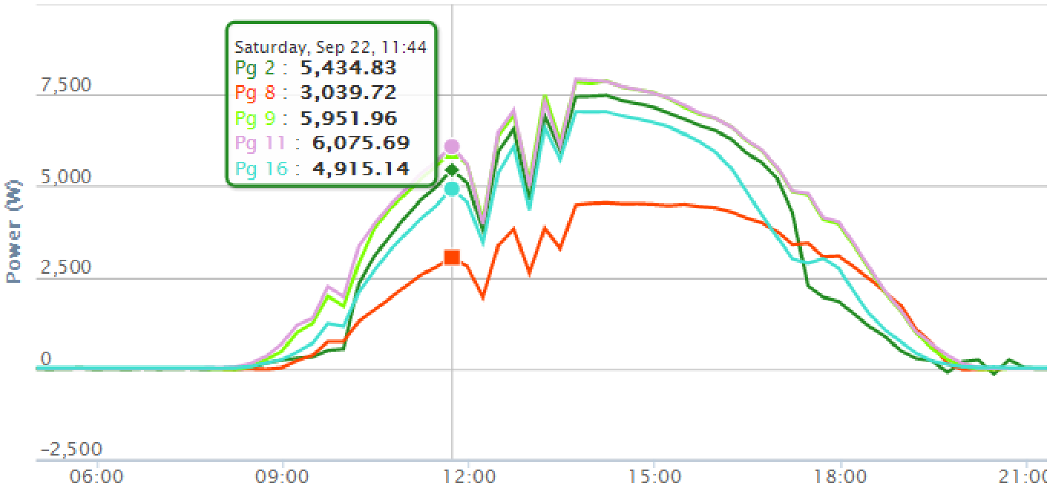


Figure 71 - Power generated by PV systems

At the sight of PV production overview of few random teams FOLD was humiliated. It is production was one of the lowest in the Vila Solar. The problem was found mostly in orientation of roof with PVT to the southwestern direction. As is seen on Figure 71 FOLD generated less during the noon but in the evening catching more of the lowest western sun.

7.8 Be 10 calculations & Energy performance label

The energy calculation program Be10 was developed by SBI (Danish national building research institute) to prove that the energy requirements of the Building Code. Approval, done by Be10, if building complies with required energy frame is required by the planning office of get the positive building permit. This tool can also help in the design phase creating a good energy concept.
Program calculates the energy use or production and according to the source of energy uses the policy coefficient for primary energy. Since FOLD used only electricity as energy that is shared with the society the coefficient is 2,5 according to BR 2010.

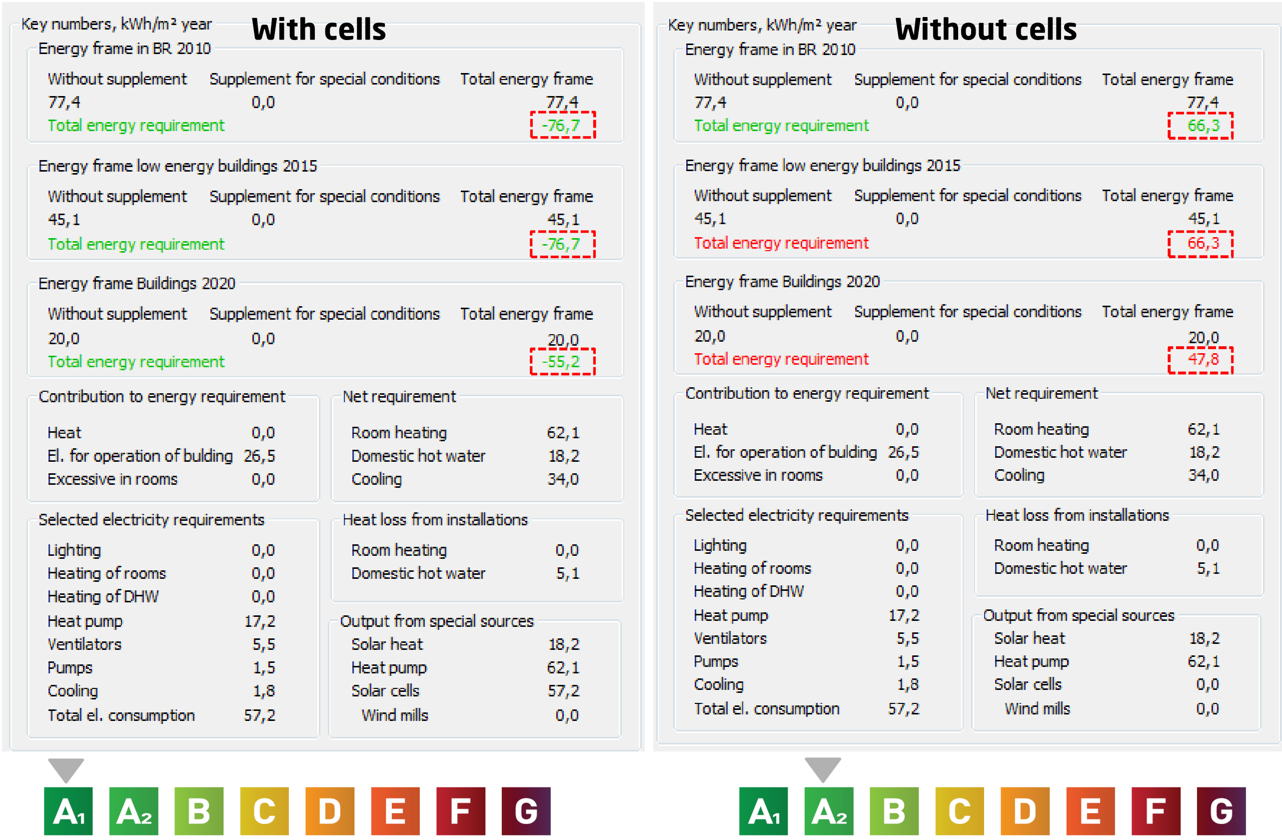


Figure 72 - Be 10 Key numbers for FOLD with and without PV cells

On the figures above are seen results of Energy performance of FOLD in Denmark according to the energy frame 2010, 2015 and 2020 with and without PV cells. The Total energy requirement when the PV cells are active is sufficient to meet all energy frames. Numbers are "green" and even negative enough to cover two houses like this.

Without PV system is FOLD capable to fulfill just requirement of energy frame 2010. It must be said that the energy load for heating is remarkably high. This most likely probably affected by too big glazed gables. The Result report and Model documentation is attached in Appendixes S.

Energy labeling is a clear way how to comunicate the result with the common person. Accroding to the Buiding Regulations 2010 a new building have to comply with enrgy class A1 or A2.

Scale			Limit kWh/m^2 year
A1	*With cells*	**-76,7**	< 30,0 + 1000/A = **45,1**
A2	*Without cells*	**66,3**	< 52,5 + 1650/A = **77,4**
B			< 70,0 + 2200/A
C			< 110 + 3200/A
D			< 150 + 4200/A
E			< 190 + 5200/A
F			< 240 + 6500/A
G			> 240 + 6500/A

Table 17 - Energy performance scale for residential buildings BR10

A is the heated area in m^2 = 66,2 (HANDBOG FOR ENERGIKONSULENTER, 2011)

Fold house was certificated as most energy efficient from Danish scale for residential buildings. In a case that the photovoltaic system is rejected and only the HVAC system stayed still the satisfactory level is achieved.

8. General discussion and conclusion

Repetition of the objectives:

- *Design, evaluation and operation the PV-T system*
- *Selection and application of low energy appliances*
- *Relation between time of energy production and energy use,*
- *Logic that apply human behavior influence to provide energy reduction*
- *Management of monitoring and testing under competition*

Partial discussions and conclusions often appeared just after the issue. Here is more generally described the contents and interlinks of this thesis.

During last year, when the FOLD house was developed, the design process was regularly consulted with the SDE organization via seven official deliveries and special checklists. Uncounted number of hours was spent extra on organization, communication and manual realization of the project. Only limited number of people endured on in the project until the very end. But no-one can regret, because every task done made us better.

8.1 Photovoltaic thermal system

Photovoltaic thermal panels were selected as a main source of energy for the DTU Solar Decathlon house. Soon was realized that none market product can fulfill the requirements on FOLD house, thus consequently started the development of new product. System design was directed by standards and requirements of competition rules. Mockup panels were thermally tested indoor under artificial sun and outdoor during the Danish summer conditions in areal of DTU campus. In the meantime, *PVT team* worked on design of electrical part and on the overall thermal system description. As found the most advantages for the thermal part, roof was divided in two arrays with horizontal strings. The final design strategy was settled when agreed to insulated PVT panels to have better control over the panel temperature. Named were two operation modes:

the heating mode when are arrays A and B circulates via drain back tank to the DHW tank. Heat removed from PVT panels is stored in the tank and the panels are cooled to lower temperature, then the ordinary PV would be;

the cooling mode when the array A continue charging the DHW tank and array B directs the flow directly to the borehole, where is cooled even more and the PV cells are provided by the lowest possible temperature to increase the electrical production.

Outcome from "Mockup testing" was to use copper piping with spacing of lateral pipes of 100mm and diameter of 8x1mm or 10x1mm in relation to each array. Manifold diameter 22x1mm. The electrical design was based of temperature division over the arrays.

After discussions with manufacturer was decided to produce the piping by own forces of *PVT team*. Sessions of outdoor testing continued with the real PVT panel A3-2. Panel underwent both thermal and electrical testing with and without active cooling via the embedded piping matrix. PVT panel was characterized by efficiency curves.

The maximum thermal efficiency of the PVT panel A3-2, with passive solar cells was measured as 48%, which was obtained when the PVT panel was cooled by the coldest fluid, which was at about 20°C. With active solar cells decreased the maximum efficiency further by about 6% to 42%.

The measurement of the electrical cell efficiency of A3-2, with grounding and cooling, showed a major change in efficiency of 2%, from an uncooled efficiency of 13.5% for a cooled efficiency of 15.5%.

Based on the efficiency curve was found the optimal flow rate in with considering the energy inputs and outputs and its effect on overall energy balance. For heating mode was declared 0,45 (l/m^{2}* min) and 0,7 (l/m^{2}* min) for the cooling mode.

Introduced was the control logic that sustains standalone service of the PVT system. Routing, connection details and piece list of all system components gave material to perform pressure drop calculations of hydraulic system. Hereafter was selected the circulation pump. PVT system was built-in the house and adjusted to steady-state operation by *PVT team*.

The junction of electrical and thermal system in one positively influences the annual energy balance even using half the space in compare to the two separate systems. Benefits of PVT panels in compare ordinary technologies were examined from energetic and economical point of view. The annual energy balance raised by 2,6% or respectively by 3,3% for Copenhagen and Madrid. The economical payback time was below 15 years, calculated very conservative way, but certainly more product price optimization is needed. To reach limit of 10 years payback time, the price should be decreased by 33% or the waste heat from water circulation should be utilized smarter way that create the overall energy savings of 33%. The current PVT system should be compared with different scenarios where is paid attention to low temperature utilization, such as coupled absorption chiller or pre-heated cold water tank connected in series with DHW tank.

For electrical production is crucial the correct choice of PV cells with corresponding power temperature coefficient. This value supposed to be low for cells in systems where is expected hot water production and conversely for low temperature heat should be chosen the cells with higher power temperature coefficient to make the cooling worthy. Conversely, the cells with lower power temperature coefficient are not that sensitive to temperature difference.

PVT systems seem to have good further potential but the right choice of suitable PVT technology and choice of the coupled system will become more important to sustain. Good combination can bring the proclaimed rise of effectiveness and let the PVT to excel the advantages compare to the " conventional solutions" .

In the FOLD house was the PVT to much compromised with the architectural concept when was not chosen the true south orientation. The overall energy concept with PVT facing South-west was feasible due to the glass gables orientation, but the current position of PVT system affected maximal power of the installed capacity. During the competition was measured the maximal energy output of 5,7 kW even with the same conditions the peak could attack level of 8kW, since the maximal system performance is 9,6 kW for STC.

The *PVT team* have done extraordinary work when in very short time managed to develop own system. Number of responsibilities and problems appeared on a daily base. Likely that no one knew the true scope of the project in the beginning.

8.2 Low energy appliances

The energy certification excludes energy use of the home appliances and lighting in residential buildings. However, for the occupant, who pays the energy, this issue might be reason to pay attention. Energy consumption for home appliances is in general significant; the share of overall energy balance is still relatively increasing because of bigger interest in to the structural improvements. Nowadays the home appliances and human behavior gets into focus.

In addition, the competition rules included this issue in very detailed description of requirements for electronic equipment that simulates the normal living in the house. The target was to fulfill all restrictions and use as little energy in the same time. During the early stage was analyzed the market with emphasis to energy verified products earning the best energy classes. The appliances were selected due to its innovation aspect, technical specifications and according to the house's foreseen use.

Home entertainment system was designed wireless based with many possibilities how to use expand and combine selected devices. At the same time, the emphasis was on simplicity even the functionality astonishes visitors but do not consume more energy than the conventional systems.

More in detail was analyzed the newly released HWC appliances (heating water circulation). Exhaustively was described their integration in FOLD house, that was very first installation in Denmark. The new way of application of HWC appliances linked with DHW tank was presented.

8.3 Human behavior and savings suggestions

In collaboration with IT team was FOLD equipped by an application informing the occupant about current energy balance and even about the past balance. It is known that just by measuring of energy can be affected the human behavior to decrease the energy use significantly. The service of application went beyond, predicts the future energy balance according to the weather forecast, and gives advices to the occupant how to behave to decrease the energy use. This extra service for occupant is a custom-made tool developed specially for FOLD house.

8.4 Energy management and timing

In relation to a good energy balance and good trade with grid, it was necessary to consider the timing. Team DTU was losing points if energy was taken from a power grid. It was very important to decrease the energy loads to minimum and apply the saving suggestions. Most of aforementioned paragraphs were based right on house energy model created in sophisticated simulation software from which was the model translated in to the spreadsheet. Here were all additional energy loads and tasks included in to the competition schedule. This simple but powerful tool clearly showed energy flows over the time, it helped to manage the energy use to optimize the correlation between production and consumption. This procedure was helpful same for the competition purpose as for the understanding of energy usage under any other conditions because the on-site energy is widely utilized. Energy produced on site do not includes the energy transport and expenditures associated with the production of energy.

Time spent on the simulation model was fully paid back during the competition period when DTU team succeeds good results in spite of additional load for the chiller. Essential was the lowered energy production (maybe also due some failures), as stated above. Nerveless the results resembled simulation made in addition, after the change. By other words, the ninth place for "Energy balance" would be replaced one of the top ranks if the situation with the chiller would not change. In the "Home electronics" category, Team DTU reached one of the five lowest consumptions; 31W was measured for TV, PC and home entertainment system. Unfortunately, it was not possible to find the true winner due to 40 W steps of SDE measurement tools.

8.5 In general

I found as superb experience when students can tune the systems and cut the energy use with real feedback on indoor climate, like in simulation software, whereas here, gets a visible response. Even the house was design with empties to low energy use, during the competition period the team found ways to go even lower.
To work on the FOLD house and be part of the team hardcore was rewarding experience. It was the best possible contact with all aspects of the energy optimizations during the house design process.

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Pressure losses *http://www.tzb-info.cz/8514-vliv-mistnich-odporu-na-tlakove-ztraty-v-potrubi*

http://www.tzb-info.cz/tabulky-a-vypocty/24-hodnoty-soucinitelu-mistnich-ztrat-t-kusy-podrobne

http://www.tzb-info.cz/tabulky-a-vypocty/21-hodnoty-soucinitelu-mistnich-ztrat-zdroje-tepla-a-zakladni-tvarovky-potrubi

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Market research on appliances:

http://www.goenergi.dk

http://www.tzb-info.cz

http://www.topten.eu

http://eartheasy.com/

http://www.savingtrust.dk

http://www.which.co.uk

http://www.uspornespotrebice.cz/

Appendixes A

Energy balance tool description

In working days between 10am and 4pm should be electricity generation higher than the el. loads. Sub-contest 4.2 Temporary Generation -Consumtion Correlation. In the spread sheet is included a draft of the task schedule. There are certain period's when the tasks can be performed and it is up to DTU team to book someone from SDE to supervise these tasks. The decision when to perform certain task can be influenced by the weather...e.g. run the Dryer between 20: 00 - 23: 00 if the electricity generation (thus also heat production) is poor during the correlation (10: 00 - 16: 00).

Each of the tasks (tasks that are scored with blue heading) has certain number of repetition. DTU team plans to have a system counting and reminds how many hours are done and when to run e.g. the Work station light.

The continuously measuring data loggers from SDE have a time step of 15min. So if runs e.g. the Home electronics (TV+DVD+PC) for 2 hours it should actually run for 2: 15 hours (7,5 min before and after) since the team do not know when the continuously measuring data logger is saving the data.

The Indoor environment (temperature, humidity and CO_2 level) are measured only in specific period. E.g. the indoor conditions are not measured between 06: 00-10: 00 and 16: 00-22: 00. So the room cooling and ventilation can be switched off between for example (6: 00-9: 00 and 16: 00-21: 00). The right time when switch on and off the system should be simulated and calculated firs otherwise can happen that the system do not provide the right condition on time. DTU FOLD house is light construction with very low thermal mass so the delay is expected very small. This way some electricity can be saved.

Functionality during the competition SDE 2012

Clothes washer

Task

The points are earned for washing laundry by running a qualifying clothes washer through one or more complete, uninterrupted, "Normal" (or equivalent) cycle(s) within a specified period of time, during which a temperature sensor placed inside the clothes washer must reach 40°C at some point in the cycle. The sensor will be continuously measuring during the washer cycle. The clothes washer shall operate automatically and have at least one wash and rinse cycle.

A load of laundry is defined as organizer-supplied 6 bath towels of weight about 2,3 kg. Only water may be used for clothes washing. No other kind of soap or similar products may be used during contest.

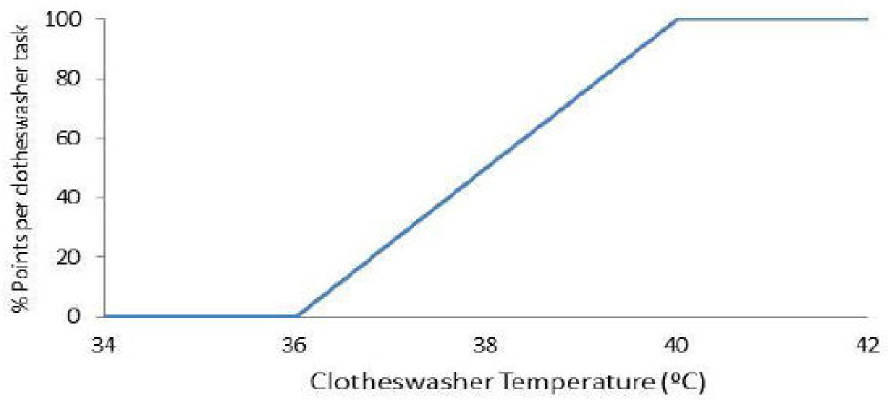


Figure 73 - Clothes washer Sub-contest points distribution

Observations and measurements

The temperature in the machine was measured with thermocouple type K placed on the glass door. Maximal temperature logged by the the SDE organisation was 38,5°C. Thus the temperature set point was increased to the 50°C. The difference regard to the previous measurement is probably due to different placement of SDE sensor.

The program 7 with HWC function had to be changed to the "Timed program 2" due to lack of countdown accuracy. The length of the program is stated to be a 1: 25 min with 50°C set point but the real time is 1: 41 min. The last minute is displayed on clothes washer screen for about 16 min during the rinse.

Practical tips for routine use after competition

- Be sure your clothes are dirty enough to really need washing. The easiest way to save water and energy with washers is to use them less, so look to ways you can reuse clothing, towels and linens between washings.
- Match water level and temperature settings on your washer to the size of your load. Don' t fill the whole tub for a few items.
- Call your water utility and ask them how "hard" or "soft" your water is. You may be using up to six times as much clothing detergent as you need. Your appliance manuals will tell you how much you need for your water type.
- For most washing applications, warm wash and cold rinse are just as effective as hot wash and warm rinse. The rinse temperature doesn' t affect the quality of the cleaning.

Dryer

Task

The points are earned by returning a load of laundry to a total weight less than or equal to the towels' total weight before washing. Clothes drying shall be completed within a specified period of time. Reduced points are earned if the "dry" towel weight is between 100.0% and 110.0% of the original towel weight. Reduced point values are scaled linearly.

The drying method may include active or passive drying (clothe line). Such a place had to be designed for that purpose.

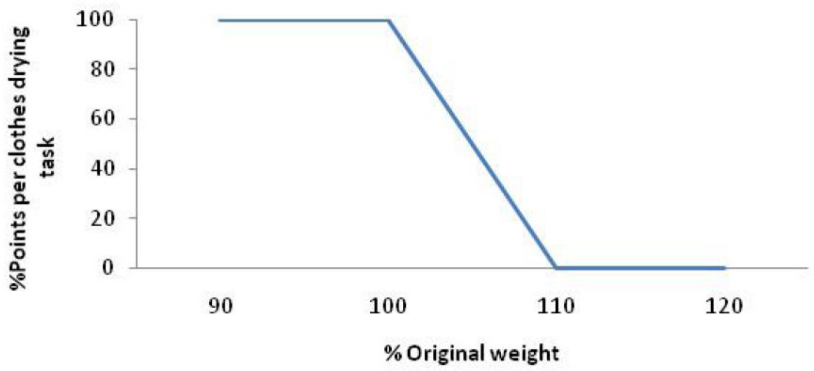


Figure 74 - Clothes dryer Sub-contest points distribution

Observations and measurements

The timed program in combination with HWC turned out to be non-sufficient to dry 6 towels of dry weight 2,3 kg completely. More time is needed. Thus during the sunny weather the towels were dried naturally outside on airer (dryer stand). This solution was proved to be fast enough to dry the towels completely. In a case of cloudy weather the drier without HWC function was used. The 3 hour time limitation is just inappropriate and non-reasonable restriction that avoids use the most efficient ways of laundry with active drying.

Practical hints for use after competition

- Clean dryer lint screen after each use. Lint build up greatly reduces efficiency.
- At least each 6 months take the lint filter out and wash it with hot soapy water and an old toothbrush. This is because the dryer sheets can coat the lint filter with an invisible film which can lead to lower dryer efficiency, a burned out heating unit and even a potential fire. To check whether there is a film on your lint screen, simply pull out the filter and run it under hot water in the sink. If the water pools up on the filter, then you need to clean it.
- Overloading the dryer lengthens drying time. Clothes should dry in 40 minutes to one hour.
- Dry multiple loads. Because the dryer takes time and energy to warm up to drying temperature, stop-and-start drying uses more energy.
- Using a clothesline, retractable rack will save energy and reduce fabric wear on your garments.

Dishwasher

Task

The points are earned by running a qualifying dishwasher through a complete, uninterrupted, "Normal" (or equivalent) cycle within a specified period of time, during which a temperature grunfos placed inside the dishwasher must reach 49.0°C at some point during the cycle. The sensor will be continuously measuring during the washer cycle.

The dishwasher should have a minimum capacity of 6 place settings. The heated drying option shall be disabled. The dishwasher may be run empty, partially loaded, or fully loaded; the load may be soiled or clean.

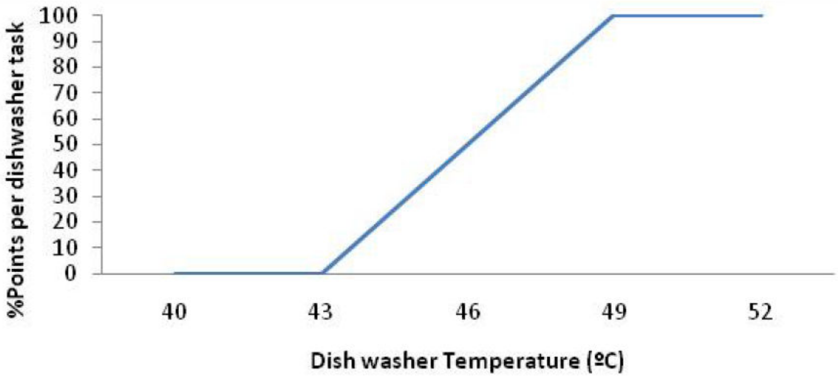


Figure 75 - Dishwasher Sub-contest points distribution

Observations and measurements

The dishwasher was loaded by 6 plates and 18 pieces of cutlery and nonetheless worked correctly according to the specifications and the time count down went precisely. But it was not really clear from the menu whether the HWC mode was chosen or if the HWC option was available neither.

Practical hints for use after competition

- Avoid unnecessary pre-rinsing before putting dishes in the washer. Modern dishwashers are very efficient and will remove all but the most stubborn food residue. Pre-rinse or soak only those dishes and cookware which won' t come clean in the dishwasher.
- Run the washer only when full to capacity.
- Clean dishwasher drains and filters to ensure efficient operation.

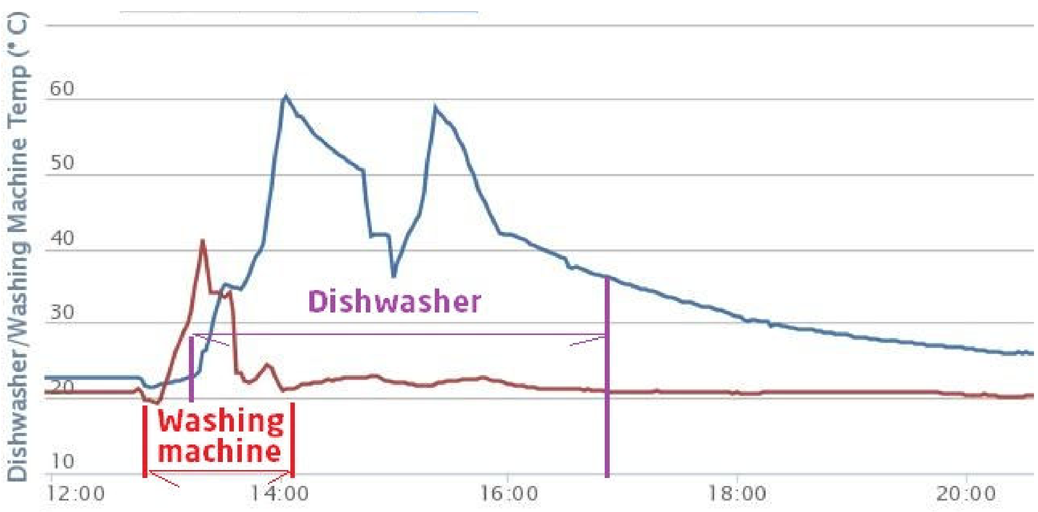


Figure 76 - Temperature measurement during the SDE competition

On the figure Temeprature is seen the temperature measurement performed during the competition period in Madrid. Washing machine ran "Timed program" number 2 for 1: 30min, 1200RPM, 50°C set point and HWC was allowed. Maximal temperature measured by SDE monitoring equipment was 41,4°C (40°C limit). Dishwasher ran the "Normal wash" program and reached 60,4°C (49°C limit).

The competition requirements were fulfilled both for washing machine and dishwasher.

Home Electronics

Task

The points are earned for operating a computer, TV and a DVD player (or video player equipment) during specified periods of time. The TV shall be a minimum of 21 in. (48.3 cm) according to the manufacturer's stated display size. The computer display shall be a minimum of 17 in. (43.2 cm) according to the manufacturer's stated display size.

All these devices have to be located in an independent circuit labeled on the electrical panel providing a 7 cm free space rail DIN next to it to locate the pulse counter.

The TV and a DVD player will be running during specified periods of time and drawing at least 90% of the baseline power during the scored period.

It is recommended to disable the functions of "Screensaver", "Stand by", or another mode that reduces the energy consumption of these devices during the scored periods.

Equipment and use

Used was the alternative of a LED TV with full HD. The Led technology provides a significantly lower use of electrical energy. As the best option was found out to use USB stick to play the video on a screen.

Brand	Samsung
Type	UE32EH4005
diagonal [´´]	32
Normal power [W]	17
Technology	LED TV
Equipped	1080p Full HD
Link	http: //www.elgiganten.dk/product/tv-radio/fladskarms-tv/UE32EH4005XXE/samsung-32-led-tv-ue32eh4005

The Raspberry Pi is a credit card sized single-board computer developed in the UK by the Raspberry Pi Foundation with the intention of stimulating the teaching of basic computer science in schools.

Brand	RASPBERRY-PI
Type	RASPBRRY-PCBA1 - SBC, RASPBERRY PI, MODEL B

Company type	RASPBRRY-PCBA1
Load power [W]	3,5
Technology	PC
Link	http: //au.element14.com/raspberry-pi/raspbrry-pcba1/sbc-raspberry-pi-model-b/dp/2081185

Brand	AOC
Type	E950SWNK
Company type	RASPBRRY-PCBA1
diagonal [´´]	18,5
Load power [W]	18
Technology	LED Monitor
Link	http: //www.cclonline.com/content/pdfs/D2rEaQO9tQ-2bPO-2bmFyx66Xg-3d-3d.pdf

Practical tips for use after competition

- Turn off the monitor when your computer is not in use. Over half of the energy used by the computer goes to the monitor, so turning it off will save significantly. A single monitor left switched on overnight can use the same energy as a laser printer producing 800 printed copies. And don't be fooled by a screensaver – the computer is still working at full power to run this.
- Turn equipment off when it is not in use. Even machines on standby use up to 30 watts of electricity.
- Printing can be the most energy-intensive step, so print only pages you need. Edit documents on-screen to save unnecessary printing. If you have a choice of printers, avoid using a laser printer for draft-quality printouts.
- Re-use paper. Inkjet printers can easily accept used paper, so you can print on the unused side. Or keep discarded pages for jotting notes.

Oven

Task

The points are earned at the conclusion of each scored period by keeping the oven temperature above or equal to 220°C during specified scored periods. A temperature sensor will be located inside the oven and will be continuously measuring every time it is turned on. The oven volume published in the manufacturer's specifications shall be a minimum of 55 liters.

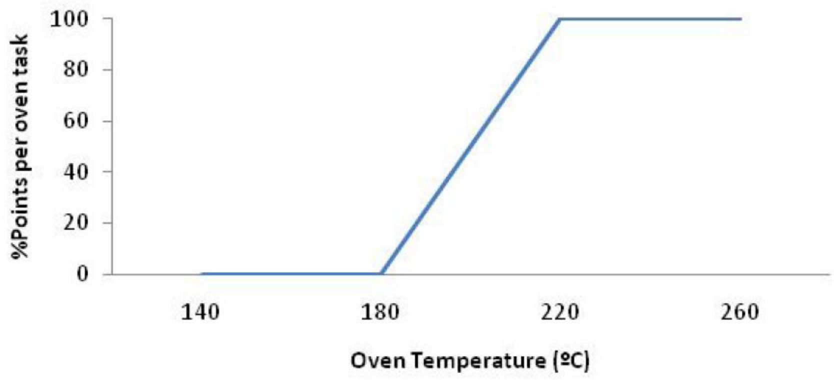


Figure 77 Oven Sub-contest points distribution

Equipment and use

This oven is a German production and offer very good performance, use value and design quality in the same time.

Brand	Siemens
Type	HB76A1260S
Volume (l)	65
Energy Use (kWh/use)	0,79
Height/width/depth (cm)	59,5/59,5/54,8
Note	Electrical Connection 3,65kW
Link	http: //www.siemens-home.se/HB76A1260S.html

Practical tips for use after competition

- Keep drip pans under conventional coil burners clean. Don' t line drip pans with aluminum foil - they can reflect too much heat and damage the elements.
- Only preheat when baking.
- Check your oven temperature. Use a separate oven thermometer to ensure your oven control is accurate.
- Make sure the oven door seal is tight. Avoid opening oven door while baking - each time the door is opened, about 20% of the inside heat is lost.
- Turn oven off a few minutes before food is ready and let oven heat finish the job.
- Use the microwave is possible. They use only 1/3 to 1/2 as much energy as conventional stoves.

Refrigerator and Freezer

Task

Refrigerator

The points are earned at the conclusion of each scored period by keeping the time-averaged interior temperature of the refrigerator between 1.0°C and 4.5°C during the scored period. A temperature sensor will be located inside the refrigerator and will be continuously measuring. The refrigerator volume published in the manufacturer's specifications shall be a minimum of 170 liters. The refrigerator may be used to store food and beverages.

Freezer

The points are earned at the conclusion of each scored period by keeping the time-averaged interior temperature of the freezer between -29.0°C and -15.0°C during the scored period. A temperature sensor will be located inside the refrigerator and will be continuously measuring. The freezer volume published in the manufacturer's specifications shall be a minimum of 57 liters. The freezer may be used to store food and beverages.

Equipment and use

This product is equipped by 1 compressor shared for the Refrigerator and the Freezer. This combined implementation makes also the space saving benefit.

We decided to withdraw from the need for devices with 2 compressors based on the message from Thursday, 9 February 2012, 11: 03 AM by Andrea Ortiz posted on SD Europe 2012 WAT in DTU Team Discussion forum.

Brand	BOSCH
Type	KGE36AW40
Refrigerator (litres)	211
Height/width/depth (cm)	186/60/65
Freezer (litters)	89
Power (W)	160
Annual Energy Use (kWh/year)	149
Note	Refrigerator +Freezer
Link	http: //www.bosch-home.dk/produkter/k%C3%B8l-frys/k%C3%B8le-fryseskabe/KGE36AW40.html?source=browse
Number of compressors	1

Practical tips for use after competition

- Adjust temperature settings for different seasons. Check refrigerator setting by placing a thermometer in a jar of water and leaving in refrigerator overnight. In the morning, the temperature should read 1 to 4,5 °C. Adjust settings if necessary. Temperature settings usually need to be reduced in winter. The freezer should be between -17,5 and -15 °C.
- During winter, freezer space often goes unused. Your refrigerator continues to use energy, however, to freeze this space. Take empty milk jugs, or other plastic containers, and fill them with water. Place

them outside until they freeze, then put them in your freezer. This will fill the empty space and reduce the area to be kept cold.
- Manual defrost refrigerators are generally more efficient than automatic defrost models, but only if they are properly maintained. The freezer should be defrosted if ice buildup is thicker than 0,5cm.
- Defrost food by putting it in the refrigerator the night before you want to use it. This will cool the refrigerator down and reduce its power consumption.
- Wait until food has cooled down before putting it into the refrigerator.
- Vacuum the coils in the back of your refrigerator twice a year to maximize efficiency.
- Check the door gasket occasionally to be sure the seal isn' t broken by debris or caked on food.
- Refrigerator should not be located near the stove, dishwasher, radiator, heat vents or exposed to direct sunlight. Check to be sure that air flow around your refrigerator is not obstructed.
- If your refrigerator has an energy-saver (anti-sweat) switch, it should be on during the summer and off during the winter.

Hob

Task

The points are earned by using any kitchen appliance to vaporize 2.3 kg of water in a single pot within a specified period of time.

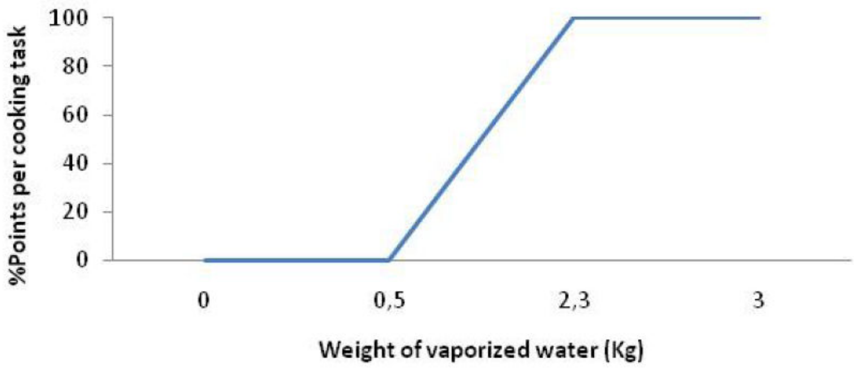


Figure 78 Cooking Sub-contest points distribution

Traditional electric cooktops use some form of electric resistance to create heat, which is transferred to the saucepan and its contents. Induction cooking is based on magnetic fields: each 'element' (an induction coil) generates a magnetic field that induces heat in steel cookware placed on top of it. In essence, the pot becomes the element that cooks the food, so the cooktop surface doesn't get as hot as other cooktops. Induction cooktops have the same instant control as gas and are the fastest of all cooktop types to heat and cook food.

Induction cooking uses 90% of the energy produced compared to only 55% for a gas burner and 65% for traditional electric ranges. Induction provides extremely fast boil and re-boil, over 50% faster than gas or electric.

Brand	Siemens
Type	EH645TE11E iQ 300

Technology	Induction
Height/width/depth (cm)	5,7/57,5/50,5
Note	Electrical Connection 7,2kW
Link	[http: //www.siemens-home.se/HB76A1260S.html](http://www.siemens-home.se/HB76A1260S.html)

Practical tips for use after competition

- Use the burner which is the closest match to pot size. Heat is lost and energy is wasted if burner size is larger than pot size.
- Use lids on pots and pans so you can cook at lower settings.
- Turn oven off a few minutes before food is ready and let oven heat finish the job.
- Induction cooktops use 90% of the energy produced compared to only 55% for a gas burner and 65% for traditional electric ranges.

Cookeware :KUHN RIKON Durotherm - 5L pressure cooker

The double-walled Durotherm system minimizes the energy required. The pot is increased by separate double-walled serving lid. This elegant serving combination is so well insulated that it keeps food hot for up to two hours.

The Durotherm also features a thick "superthermic" sandwich base, fully encapsulated in quality 18/10 stainless steel to ensure even cooking with no burning hot spots. Designed to impress - it is elegant, efficient, quiet and easy to maintain with an emphasis on user friendliness and short handles that make it easy to store away. Additionally, 5 built in pressure-release and automatic lid locking systems make this pressure cooker 100% safe.

This double wall pressure cooker supposed to save a lot of energy by cooking with higher pressure. This way we can use les power to evaporate the same amount of water.

Figure 79 Pressure cooker

Cooking task

The task is to vaporize 2,3kg of water in a single pot with starting water weight at least 2,75kg.

The water is vaporized from 5l pressure cooker (Kuhn Rikon Duratherm) on electrical induction hub (Gram IN 6001 T). Induction cooking utilizes 90% of the energy. Efficiency of cooking is estimated as 85%. The heating element with diameter 22 cm and power output of 2,3 kW can perform the task in 15 minutes using 575 Wh of electricity.

Cooking process contains from 2 parts: a) reach the boiling point and b) vaporize 2,3 kg of water.

a) Energy to reach the boiling point

$$E_{boil} = m \cdot c \cdot \Delta t = 2{,}7kg \cdot 4186 \frac{J}{kg \cdot K} \cdot (100°C - 15°C) = 978\ 477{,}5\ J$$

b) Vaporize 2,3 kg of water (lv is enthalpy of evaporization of water)

$$Lv = l_v \cdot m = 2\ 257\ 000 \frac{J}{kg} \cdot 2{,}3\ kg = 5\ 191\ 100\ J$$

$$E_{ideal\ cooking} = L_v + E_{boil} = 978\ 477{,}5J + 5\ 191\ 100J = 6\ 169\ 577{,}5\ J$$

$$P_{\mathrm{cooking}} = \frac{6\ 169\ 577{,}5\ \mathrm{J}}{3600\mathrm{s}} = 1713{,}8\ W$$

Determination of cooking time and electrical energy use

$$P_{heating\ element} = \frac{1}{\mu} \cdot \frac{\mathrm{P_{cooking}}}{\mathrm{t_{cooking}}}$$

$$2300W = \frac{1}{0{,}85} \cdot \frac{1713{,}8}{\mathrm{t_{cooking}}} \gg \mathrm{t_{cooking}} = \frac{1713{,}8}{0{,}85 \cdot 2300} = 877s = \mathbf{14{,}6\ min}$$

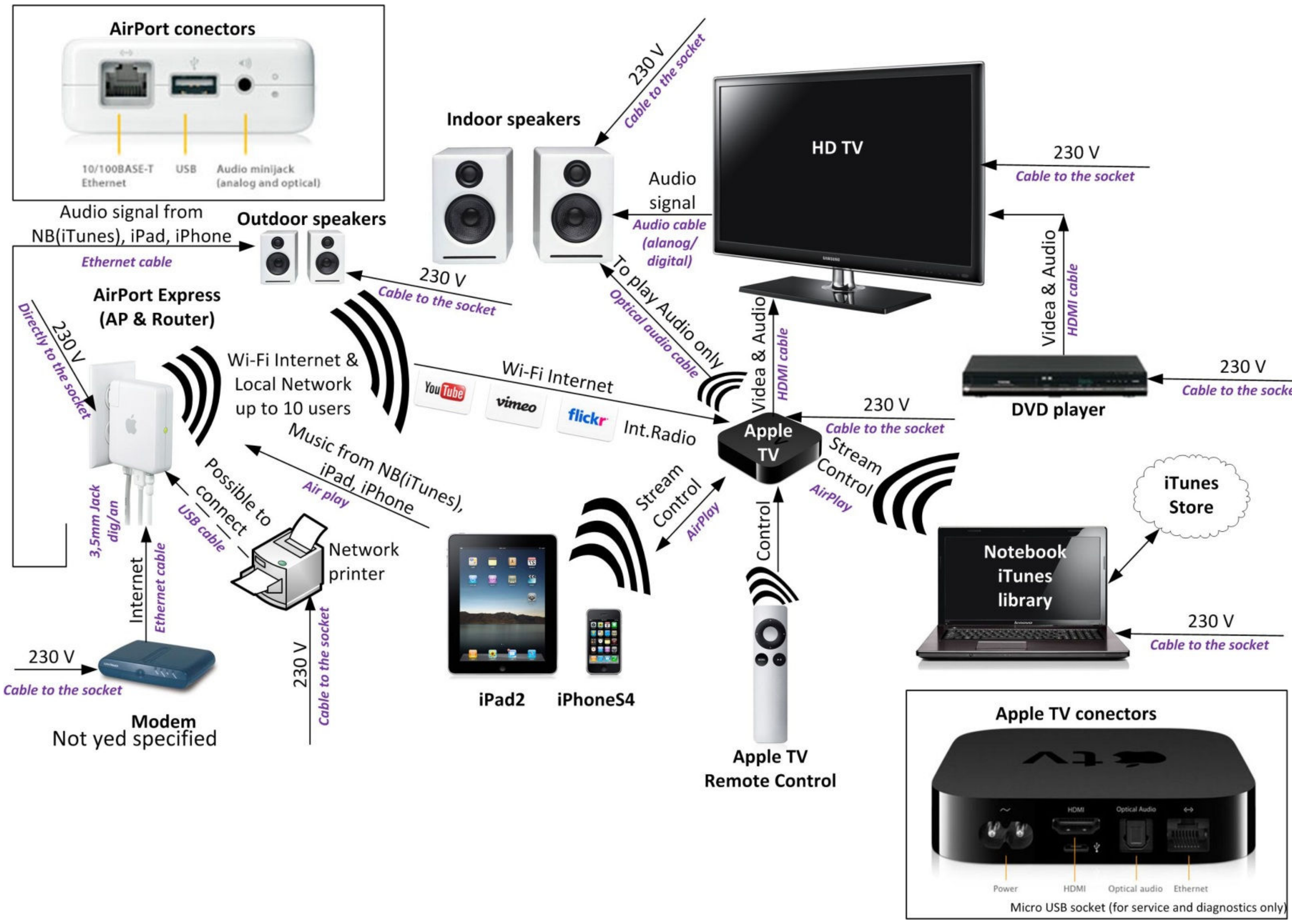
$$E_{cooking} = P_{heating\ element} \cdot \mathrm{t_{cooking}} = 2300W \cdot 0{,}25h = \mathbf{575Wh}$$

Home entertainment system

The home entertainment system isn' t mandatory by the rules. However for purposes of the public visits and also for the required dinner party is desirable to have such a system in the house.

Because the device iPad2 by Apple has been preselected to control functionality inside the house and influence a human behavior. We decided to use the entire home system by company Apple called **AirPlay** provided through products **Apple TV** and **AirPort Express**. This way we can use only one device to browse internet (control the house based on webpage access) and control and stream multimedia we want to audio & video inside/outside the house. Likewise the Apple systems are known as proofed and reliable working systems without unexpected failures.

The setup, seen below on Scheme 1, is not a common use of the Apple systems. The components were studied individually and the final Scheme 1 was discussed with IMM group. Also it is wanted to discuss our setup this with Apple' s representatives in Denmark.



Scheme 1 Home entertainment system

Description of the Home entertainment system

AirPlay 

AirPlay is a way to wirelessly stream audio, video, and photos. Devices currently implementing AirPlay are of two categories: the devices that send audiovisual content, and the devices receiving the content and render it on display and/or speakers:

- AirPlay sender devices include computers running **iTunes** and iDevices such as iPhones, iPods, and **iPads** running iOS4.2 or greater.
- AirPlay receiver devices include **the AirPort Express** (that has an audio output through a jack connector), the **Apple TV,** and third party speakers.

Speakers attached to an AirPort Express or Apple TV can be selected from within the "Remote"[4] iPhone/iPod Touch application, allowing full AirPlay compatibility.

AirPort Express

The Airport Express functions as a wireless access point (wireless router) when connected to an Ethernet network. It can be used as an Ethernet-to-wireless bridge under certain wireless configurations based on the IEEE 802.11standard (also known as Wi-Fi).

The AirPort Express allows up to 10 networked users, and includes a feature called AirTunes (predecessor to AirPlay). It includes an analog–optical audio mini-jack output, a USB port for remote printing or charging the iPod and a single Ethernet port.

Apple TV

The Apple TV is a digital media receiver that allows streaming audio and video from a iOS device or from a computer (Mac or PC) using iTunes.

Apple TV outputs video through an HDMI port. Audio is supported through the optical and HDMI ports. The device connects to the internet and local networks through an Ethernet or Wi-Fi connection. The device also has a Micro-USB port, but this is reserved for service and diagnostics.

Apple TV can function as a peer-to-peer digital media receiver, streaming content from the iTunes Store, YouTube, Flickr,... or any Mac OS X or Windows computer running iTunes onto an TV over AirPlay.

Functionality

Our Notebook (Mac or PC) will be connected to the Apple TV over AirPlay and we could stream presentation, photos from assembling of the house or just video clips during the Exhibition or Party dinner on the HDTV screen.

Interior speakers can work independently when it is connected via optical audio cable to the Apple TV. The outdoor speakers will be connected to the remote AirPort Express unit. This way will be created 2 independent audio zones both controlled from one place and wirelessly.

Audio and video can be streamed from all iOS devices (iPad, iPhone or notebook running iTunes).

Public tours scenario

We have **3 iPads**.

- One is for show up during the tour inside the house. The two left will be used on the west facade (people will end the tour here).

We have **2 TV´s**

- The 32´´ TV will be inside the house for the competition task and another one will be placed outside on the east facade where the people queue.

What the 1 inside iPad do: Is connected to internet and showing the IMM control system, web page with the energy balance and have a docking station on a wall.

[4] http: //www.apple.com/itunes/remote/

What the 2 outside iPads do: iPad´s will take a picture with FOLD model of guy standing in front of it (just touch the button – advice to take a picture with fold and explanation of what will happen after) and the picture will be uploaded to FB gallery (only people in „like it" status will be able to see that on FB).

What the inside TV do: The TV is playing DVD and have the Apple TV for reason of the show up during the dinner.

What outside TV do: The TV on the other side of the house (queue line side – East side) will display 5 pictures of people after the tour, each for 5 seconds and then it will switch to the energy balance screen (taken from internet as well - probably).

So basically make a Java app collecting data for slideshow on a webpage (if possible). The TV can be a Smart TV that can browse Internet

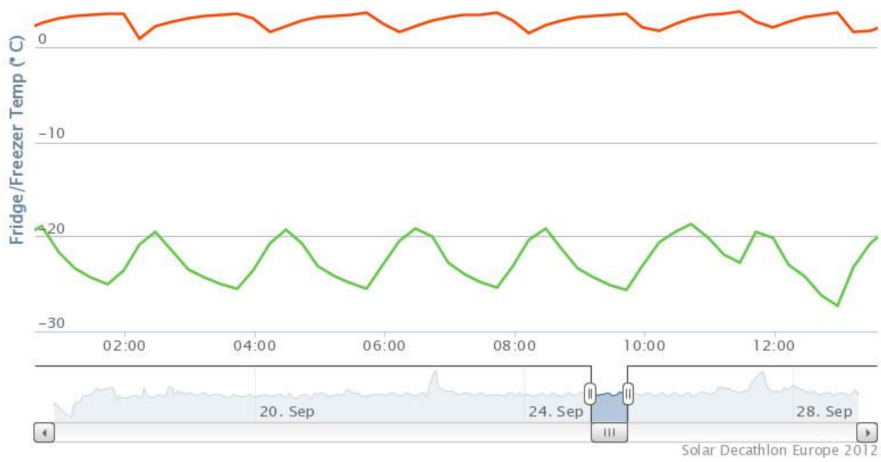
http: //www.elgiganten.dk/product/tv-radio/fladskarms-tv/UE32ES5505XXE/samsung-32-led-smart-tv-ue32es5505

If it´s difficult to make a Java that the TV will display exactly what we wants. Then probably some PC (Rapsberry Pi inside th house if the SDE allows) will do that and display that on a normal TV

Refrigerant and freezer

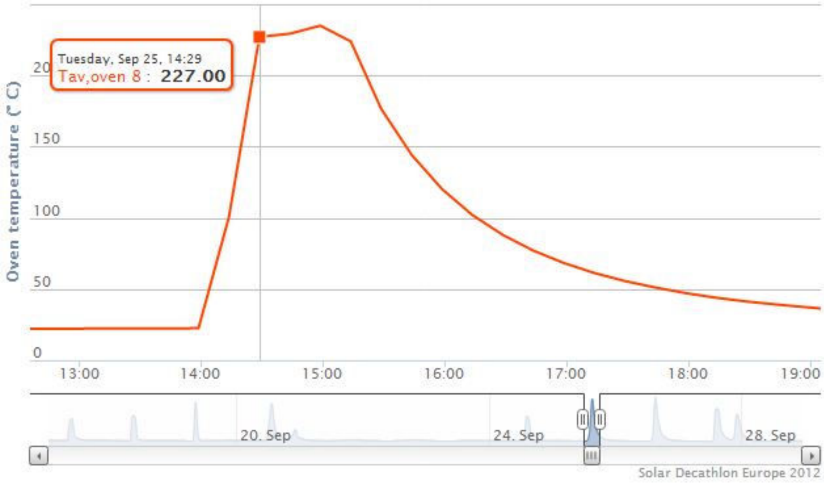
The full score was received when the temperature in the refrigerant did not fluctuated out of range between 1 and 4,5°C and from -29 up to -15°C in the freezer.

Measurement results (seen on Figure Refrigerant) logged every 15min showed well-chosen temperature set points and the goods as well. Temperature inside the units very rarely went out of the scored range. The reason was mostly opening of the unit is doors and filling/emptying of the units.



Oven

This sub-contest requered to reach during 45min within 1hour temperature range from 180 to 220 °C or more to get full points. As seen on figure (Oven measurement) the desired temperature was reached about 20min after the oven was started. This starting process was not possible to speed up even after all plates have been removed and the ventilated was turned on.



Heat pump circulation

From the NILAN Compact P certificate (Appendix D) is seen that the thermal output for reheating the DHW tank is 0,83kW (for average annual temperature in Denmark).

Then if the thermal output duration is 1h the energy delivered is then 0,83kWh = 830Wh/60min =13,833 W/min delivered to the appliance.

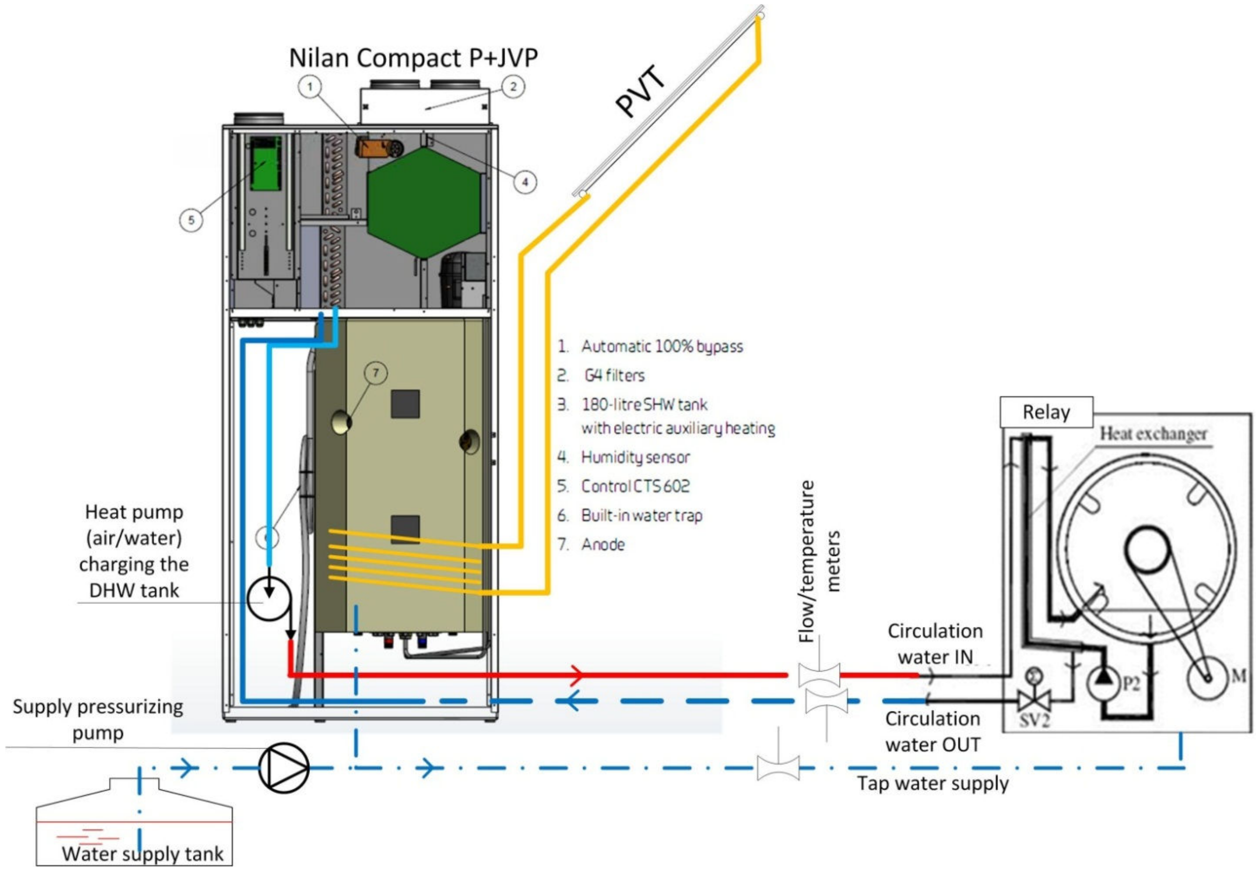
For HWC appliances is relevant flow rate of 1,6 l/min (1,6 kg/min).

$E = m * c_w * \Delta$ **t**

13,833= 1,6* 1,163* Δ **t** then delta t= **7,43K**

The previous measurements showed that average temperature difference for clothes washer was 50,56 / 31,54°C. Thus the return circulation water would be heated up just by 7,43K to about 39°C. Clothes washer tolerates for HWC supply temperature up to 7K lower than the requirement of 55°C, thus 48°C. The circulation water reheated by HP would then be too low for the unit.

The solution would be to change logic of the ASKO appliances when would be allowed to run HWC with lower supply temperature and circulate longer. Another option is to decrease the flow rate for circulation thus the inlet temperature would rise up.



Appendix B - Appliances technical specification

Clothes washer AskoW6884 HWC   Overview of tech. specifications

Brand	ASKO
Type	W6884 HWC
Water consumption (liters)	65
Height/width/depth (cm)	85/ 59,5/ 58,5
EL. Energy Use (kWh/wash)	0,5
Annual Energy Use (kWh/year) year=200 cycles	100 kWh/year (HWC connected), 240 kWh/ year (electricity use only)
Total power (W)	2200
Link	http: //www.asko.se/hwc/hwc-produkter/

Programtabell

Program	För-tvätt	Temp. °C	Antal Skölj-ningar	Varvtal v/min	Max last (kg)	Vattenförbrukn. (ca liter)	Energiförbrukn. (ca kWh)	Programtid (ca tim och min)
1. Automatprogram		1)						
2. Tidsprogram								
3. Grov- med förtvätt	X	95	5	1800	8	85	2,2	2:45
	X	60	5	1800	8	75	1,1	2:40
4. Normal vit/kulört		60 2)	3	1800	8	65	1,10	3:20
		40 3)	3	1800	8	65	0,67	2:57
5. Snabb vit/kulört		60	3	1800	8	60	1,2	1:40
6. Kvicktvätt		40	2	1800	4,0	25	0,4	0:45
7. Strykfritt/sport (Easy care)		40 2)	2	1200	4,0	50	0,5	1:20
8. Syntettvätt		40	3	800	2,5	30	0,4	1:20
9. Ylle/handtvätt		30	3	800	2,5	70	0,5	0:50
10. Sköljprogram			1	1800	4,0	15	0,1	0:20
11. Centrifugering				1800	4,0	0	0,1	0:15
12. Utpumpning								0:01

1) Kort program för testinstitut, max 1/2 last.
2) Testprogram med kallvattenanslutning enligt EN 60456. Vid stora tvättmedelsvolymer rekommenderar vi att man tar ut insatsen och doserar direkt i tvättmedelsfacket.
3) 40 °C program för testinstitut. Tillvalsfunktion 40 °C måste väljas.

Förbrukningsvärdena gäller maskin som inte är kopplad till värmevattensystemet. I tabellen ovan redovisas några exempel på förbrukning av energi, vatten och tid för några olika programinställningar. Förbrukningsvärdena kan variera beroende på vattentryck, vattnets hårdhetsgrad, temperatur på inkommande vatten, rumstemperatur, mängd och typ av tvättgods, variationer i elnätet samt valda tillvalsfunktioner. Vid de exempel som redovisas här har inställningen för skölj varit Normal och inga tillvalsfunktioner har använts.

Om du använder stora mängder tvättmedel, exempelvis icke kompakta pulver, och upplever att den mängd du vill använda inte ryms i facket, kan du lyfta ur insatsen och dosera direkt i facket. Vi rekommenderar alla testinstitut att ta ur insatsen vid stora tvättmedelsvolymer.

Energiförbrukning och programtider för HWC*-ansluten tvättmaskin

* Heating Water Circuit (värmevattenkrets)

Program	Inställning	Temp. °C 1)	Förbrukningsvärden 2)	
			Programtid (ca timmar:minuter)	Energi (ca kWh)
Normal vit/kulört, 60 °C	Eco	55	4:10	0,4
Normal vit/kulört, 60 °C	Auto	55	3:50	0,5
Normal vit/kulört, 60 °C	Quick	55	3:15	0,9
Normal vit/kulört, 60 °C	Eco	80	3:20	0,2
Normal vit/kulört, 60 °C	Auto	80	3:20	0,2
Normal vit/kulört, 60 °C	Quick	80	3:10	0,8

1) Temperatur på inkommande vatten till värmevattenkretsen.
2) Vid ovan angivna värden är flödet för värmevattnet 1,6 liter/minut.

Dryer Asko T784HWC

Overview of tech. specifications

Brand	ASKO
Type	T784HWC
Dryer system	Vented (Exhaust)
Height/width/depth (cm)	85/ 59,5/ 59,5
Energy Use (kWh/cycle)	0,4 kWh (HWC conected) 3,51 kWh/year (electricity use only)
Annual Energy Use (kWh/year) Year= 81 cycles	284 kWh/year (electricity use only)
Total power (W)	2250
Link	[http: //www.asko.se/hwc/hwc-produkter/](http://www.asko.se/hwc/hwc-produkter/)

För nedan angivna förbrukningsvärden gäller följande förutsättningar:

Tilluftens temperatur:	23 °C
Tilluftens fukthalt:	55 %
Torktemperatur:	Normal
Elementeffekt:	1950W, 10A

Program	Material	Last	Centrifugeringsvarvtal (v/min)	Energiförbrukning ca (kWh)	Programtid ca (min)
Auto extratorrt	Bomull, linne	1/1	800 rpm	4,0	2:10
			1000 rpm	3,8	2:05
			1400 rpm	3,3	1:50
			1600 rpm	3,1	1:45
Auto skåptorrt	Bomull, linne	1/1	800 rpm	3,9	2:00
			1000 rpm	3,6	1:50
			1400 rpm	3,1	1:35
			1600 rpm	2,9	1:30
	Strykfritt, polyester/ bomull	1/2	1000 rpm	1,8	1:00
Auto normal-torrt	Bomull, linne	1/1	800 rpm	3,8	1:50
			1000 rpm 1)	3,51	1:45
			1400 rpm	2,8	1:30
			1600 rpm	2,5	1:15
	Strykfritt, polyester/ bomull	1/2	1000 rpm 1)	1,30	0:45
Auto stryktorrt	Bomull, linne	1/1	800 rpm	3,7	1:35
			1000 rpm 1)	3,03	1:25
			1400 rpm	2,4	1:05
			1600 rpm	2,0	0:50

1) Testprogram enligt EN61121:2005. Vid test ska torktumlaren kopplas 16A och tillvalet Tidsbesparing ska vara inkopplat. Textilierna ska efter tvättning vara centrifugerade vid 1000 v/min.

Dishwasher Asko D5654 SOF HWC

Brand	ASKO
Type	D5654W HWC
Water consumption (litres)	9,9
Height/width/depth (cm)	82/59,6/55,0
Energy Use (kWh/cycle)	0,16 kWh (HWC conected)
Annual Energy Use (kWh/year) year=280 cycles	44,8 kWh/year (HWC) 296 kWh/year (electricity use only)
Total power (W)	1700
Link	http: //www.asko.se/hwc/hwc-produkter/