MacSheep
25% energy savings
for solar and heat pump systems

Final Project Summary Report – 26 February 2016

MacSheep - New Materials and Control for a next generation of compact combined Solar and heat pump systems with boosted energetic and exergetic performance

Dissemination Level: PU – public

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Executive Summary

The main goal of the MacSheep project was the development of solar and heat pump systems performing 25 % better in terms of electric energy demand, compared to state of the art benchmark solar and heat pump systems, while still being competitive in terms of prices for the end-consumer. A second goal was the improvement of whole system test methods that can be used for energetic benchmark testing of hybrid systems and for the replacement of field testing in system developments. The focus is thereby on small compact heat production units that deliver space heat and domestic hot water for a single family home, with possible extension of the concepts to multifamily dwellings.

In order to reach the energetic and economic targets for these solar and heat pump systems, breakthroughs in the field of solar collectors, heat pump technology, compact storage and intelligent control were further developed and implemented into prototype products. In the first year of the project, the cost-effectiveness of potential breakthroughs was analyzed by means of cost estimation in combination with annual system performance simulations. The most promising breakthroughs have been selected for component developments and implementation into four full functioning solar and heat pump systems. The components for solar and heat pump systems that were developed within the MacSheep project included:

- A selective glazed PVT collector that can be used to supply both heat and electricity for a solar and heat pump system.
- A new selective unglazed collector that is cheaper in production and can thus be sold in larger areas for the same price as previous solutions.
- Four heat pumps designed for different target heat loads and different system concepts, two of them using the newest generation of speed controlled scroll compressors. Two of these heat pumps are equipped with economizer cycles, two of them with a desuperheater for domestic hot water preparation, and one with a storage integrated condenser.
- Three new storage tanks, one with an integrated heat pump condenser, and all three with enhanced stratification capabilities for the combination with heat pumps. For two storage tanks heat losses have been reduced with VIP insulation.
- Control algorithms that use domestic hot water tapping forecast, fault detection, and ICT for communication with the user or the installer.

Three of the four developed concepts of solar and heat pump systems were built as full systems during spring 2015, and evaluated with whole system test methods in order to demonstrate the achievement of the goals of the project. The evaluated key performance figures were the annual electricity consumption of the entire system for a given heat demand profile, and the annual system price that includes installation, maintenance, and electric energy purchase.

The final results show that two of the four systems were able to meet or pass the target of 25 % electricity savings for the load and climate for which they were optimized, and one of the four systems reached close with 24 % and good potential to increase to 26 % with further simulated improvements made. The fourth system reached 15 % savings, which is still a very good achievement considering that in this fourth case a first route of development with an already built prototype had to be abandoned during the project, and less time was then available for the development of a new system and prototype. All systems were shown to be cost-effective for the heat loads that they were designed for.

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1 Context and Main Objectives

The current production of heat for domestic use in Europe is largely based on imported fuels such as non-renewable carbon rich sources (Eurostat 2009, p. 452). This results in ***large emissions of greenhouse gases*** and other air pollutants. The current practice is not sustainable. Therefore, EU energy politics strongly accent a rapid transition to energy efficient buildings that cover their heat demand mostly from local renewable energy sources, minimizing thereby primary energy inputs. The European EPBD directive (EPBD recast 2010) implies an “almost zero energy building" standard for new buildings by 2021. This trend is expected to result in building integrated ***multifunctional and hybrid renewable energy devices***, such as solar thermal / photovoltaic collectors, and ambient energy heat exchangers, combined with efficient heat pump systems.

In most European countries solar thermal collectors are used increasingly for the production of space heat and the preparation of domestic hot water (SH+DHW). Whereas the sales of oil and gas boilers are decreasing, the ***sales of heat pumps*** are steadily increasing (EHPA 2010) and have ***already surpassed those of oil and gas boilers*** in Switzerland and Sweden. Heat pumps can provide heat all year around using ground source or ambient air as a heat source with a seasonal performance factor (SPF) of 2.5 to 4[1], i.e. the heat output of these systems is 2.5 to 4 times greater than their electricity consumption. The electricity demand of heat pumps is an important factor for the evaluation of the sustainability of these systems, and it is sometimes claimed that heat pumps are only as sustainable as the electricity production needed to run them. In comparison, solar thermal collectors have a heat to electricity ratio of 100 or more, but cannot provide enough heat over the whole year without seasonal storage. Therefore, ***solar thermal collectors improve the efficiency and sustainability of combined solar and heat pump systems***, which is of utmost importance since a full coverage of the increasing electricity demand of Europe with renewable energies is still far away.

The overall objectives of the MacSheep project were to ***develop new innovative products and test methods*** for a next generation of compact hybrid ***solar thermal systems coupled with heat pumps***. These systems are using breakthroughs in the field of solar collectors, heat pump technology, compact storage and intelligent control in order to achieve ***25% energy savings*** compared to the state of the art of solar and heat pump systems at the beginning of the project in 2012, under identical boundary conditions of heat load and climate. Produced and sold in large numbers, it shall be possible to sell these systems with ***competitive prices*** on the market. The focus is thereby on small compact heat production units that serve a single family home, with possible extension of the concepts to multifamily dwellings.

With “compact” it is meant that these systems do not require more than 1 m^3 of energy storage volume in the building, and that a manufacturer is able to ***pre-fabricate the central heat storage and heat management unit*** that is installed in the building to a large degree, such that only ***little work has to be done on site by the installer***, improving thus the ***ease of use, reliability*** (avoidance of installation faults) and the chances for ***market penetration***.

[1] The SPF of the system is defined as the useful heat delivered by the system divided by the total electricity demand of all compressors, pumps, control units etc. The SPF of heat pumps, and thus also of the system, depends strongly on the temperature levels of the heat supplied and of the heat sources available. Therefore, it can only be compared with other systems if they supply equal amounts of heat at equal temperatures with the same boundary conditions for climate and for available heat sources. For this reason, all values for SPF mentioned can be exchanged for higher values – for the same systems under more favorable boundary conditions of heat use and climate – or for lower values – for systems with less favorable boundary conditions of heat use and climate.

The project used a ***systematic approach for improving the performance/cost*** ratio for solar and heat pump systems. This approach was splitting the work into four phases:

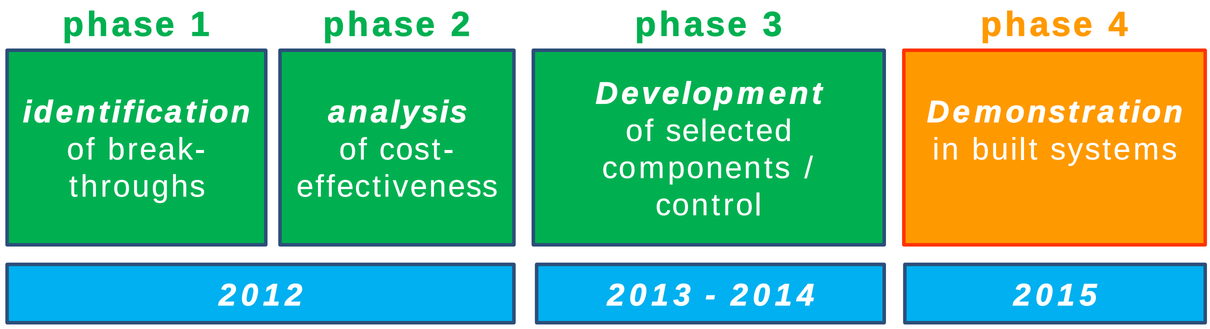


Figure 1: Phases and time-line of the MacSheep project.

Within the first 6 months of the project (phase 1) a review of breakthroughs for the different components (collector, heat pump, storage, control) in solar and heat pump systems was performed. In total, 43 breakthroughs were selected for the more detailed analysis by system simulations in phase 2. At the same time, within WP2, the current state of the art of whole system testing applied in the different institutes that are partners in the MacSheep project were described, and a harmonization of the similar – but yet quite different - whole system test methods have been undertaken. Agreements were reached on important questions such as the system boundary of the tested heating systems and the boundary for load and climate.

Within phase 2 of the project (month 7 to 12), the expected cost-effectiveness of the 43 selected breakthroughs was determined with transient system simulations and estimation of additional (or decreased) cost of the system. Based on these evaluations, the 20 most promising breakthroughs were selected. In parallel, two state of the art solar and heat pump heating systems – one with an air source heat pump and one with a ground source heat pump – were tested in this phase of the MacSheep project in order to be used as a benchmark.

Within phase 3 of the project (month 13 to 36), the four development groups of the MacSheep project have implemented the selected breakthroughs into new component prototypes. These prototypes were tested and improved in the laboratory, and simulation models were further developed and calibrated with the lab measurements. Few of the selected breakthroughs had to be abandoned and replaced because of low performance that was shown after first developments in the lab in combination with the calibrated system simulations. At the same time, the whole system test methods were further harmonized, simplified, and improved. A shorter test cycle of six days instead of twelve days has been developed and verified, and a solution has been found that allows for identical space heat loads of the different tests while at the same time letting the tested system control the space heat distribution pump and valve separately.

Based on the component developments, four full Solar and Heat Pump Systems have been proposed at the end of phase 3, of which three were built and tested with whole system test methods in 2015. The four systems include ground source, air source, and solar source heat pumps, and include solutions for low heat demand houses with low space heat supply temperatures as well as refurbished houses with higher supply temperatures. At the same time, the applicability of improved whole system test methods was to be demonstrated in this phase of the project.

2 Main S & T results / foregrounds

The MacSheep project followed a systematic approach for the selection and development of breakthroughs for components of solar and heat pump systems. This approach was based on the estimation of additional cost for new component design, in combination with annual simulations for the determination of the energetic benefit for the whole system. Thus, at the end of phase 1 of the MacSheep project, the breakthroughs that were thought to improve the overall system performance were critically evaluated in the light of their cost-effectiveness. Only breakthroughs and component developments that showed to be cost-effective were selected for a further development and implementation into MacSheep solar and heat pump systems. Cost-effectiveness thereby can be achieved by two ways: one way is through electric energy cost savings that outweigh a possible increase in system installation and maintenance cost. The other way is by installation or component cost savings that go along with a slightly worse energetic performance of the system, but allow for investing the saved money on other parts where the system's energetic performance can be improved more cost-effectively. A more detailed description of this systematic approach for improving not only the energetic performance, but also the cost-effectiveness of the systems, can be found in the deliverables of the public deliverables of the project that are available for download under www.macsheep.spf.ch.

2.1 Advanced collectors for solar and heat pump systems

In the MacSheep project two solar collector prototypes have been developed by the partners ESSA and CTU. These prototypes include breakthroughs which have been identified and analyzed within phase 1 and phase 2 of the project.

2.1.1 Development by Energie Solaire SA

Energie Solaire SA (ESSA) is probably the only manufacturer of selective unglazed collectors in the world. These collectors can be used well as a heat pump source directly or in combination with a small / medium ice storage. The omitted glazing leads to a much better heat transfer between collector and ambient air, compared to glazed collectors. Thus, it is possible to use these collectors also as air source heat exchangers when there is little or no sunshine available. The MacSheep system developed by ESSA, IWT TUG & HSR SPF uses the unglazed collectors as only heat source for the heat pump, replacing the traditional ambient air heat exchanger. Thus, the collectors represent a key component of the new system development.

Within the MacSheep project ***ESSA*** has developed a new absorber made of ferritic stainless steel with a new selective paint that is applied on the stainless steel coils (coil coating) before the stamping and welding process. The geometric design of the unglazed collector (absorber with cushion geometry and full irrigation) remains the same as for the current ESSA solar collector design.

Two new selective paints have been tested and compared with the benchmark collector, based on the comparison, one of them has been chosen for further developments. For a typical value of $(t_m - t_a)/G = 0.025$ for the given application the new selective paint performs between 11 and 14 % less than the benchmark product. However, when the new collector performance parameters are implemented in the annual simulation of the solar and heat pump system with series collector heat use, the electric energy demand of the system only increases by 2 %

compared to an annual simulation with the ESSA benchmark collector parameters. Due to significant cost savings with the new absorbers, a larger collector surface can be installed for the same price, leading to a better system performance than with the smaller area of the previous collector design.

ESSA tested the new coated collectors in the field at different outdoor conditions (chlorine environment, saline air, gas burner exhaust) for durability under stagnation. After 5 months duration of these exposure tests, the coating of the test samples showed no damage. Outdoor exposure tests will continue after the MacSheep project.

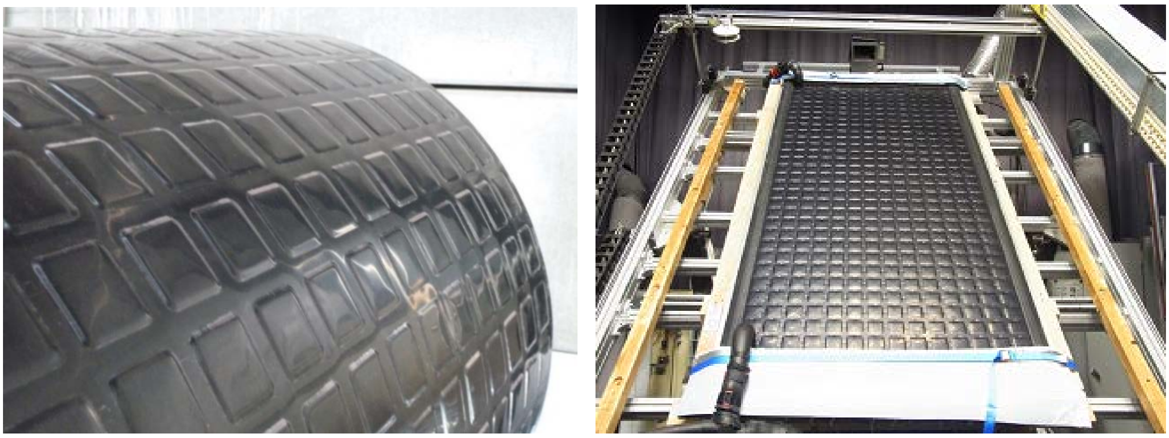


Figure 2: Ferritic stainless steel coil with new selective paint (after stamping of cushions), and absorber made with the new coating under test.

2.1.2 Glazed PVT collector development by CTU

CTU has developed a new design of a glazed hybrid photovoltaic-thermal (PVT) collector with polysiloxane gel as encapsulation compound for PV cells in the frame of the MacSheep project. This collector provides heat and electricity simultaneously within the MacSheep solar and heat pump system developed by CTU and Regulus. Heat can be used directly for storage tank charging, electricity can be used both to cover the electricity consumption of the solar heat pump system and for charging the upper part of the storage to temperatures of up to 90 °C by an electric heater.

Polysiloxane gel has been chosen for the encapsulation because of its high temperature resistance in combination with other important features such as high solar transmittance, high thermal conductivity, electric insulation, and low modulus of elasticity. The polysiloxane gel encapsulation machine that is available at the University Centre for Energy Efficient Buildings (Czech Technical University, CTU) was used to produce different glazed PVT collector prototypes. The encapsulation technology is based on low vacuum dosing of the gel into the gap between the glass pane and the flat heat exchanger with immersed strings of PV cells. The encapsulation process is carried out at room temperature. This fact brings a clear advantage for future production of the hybrid PVT collectors.

Several different prototypes of glazed PVT collector have been fabricated and tested at outdoor and indoor (sun simulator) conditions. Based on the experience from the tests and the new encapsulation process, the final design of the glazed PVT collector has been adapted and optimized.

A double glazing, consisting of two solar glass panes, was used for the spectrally nonselective and selective alternatives of the final PVT collector (see Figure 3). The original version of the spectrally selective PVT collector was fabricated from double glazing with a standard coating with low-emissivity in the infrared part of the spectrum and reduced transmittance in the near infrared region of solar radiation. The final prototype used double glazing with an argon filled gap of 30 mm between the glass panes. A low-e coating with high solar transmittance was applied to the absorber glazing to achieve low heat losses.

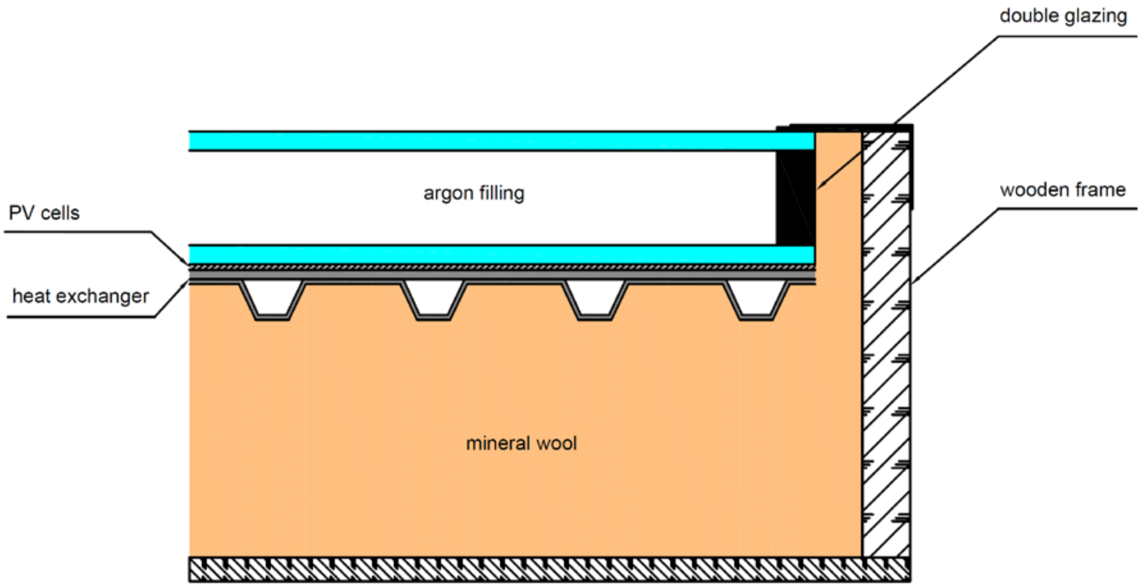


Figure 3: Layout of the glazed hybrid PVT collector.

Large effort has been dedicated to the development of the encapsulation process and to the search for suitable materials for sealing, distance elements between the glass and the absorber sheet, and electric contact sleeves that are compatible with the polysiloxane gel.

The final construction design of the developed glazed PVT collector is based on monocrystalline silicon cells 125 x 125 mm with a nominal efficiency of 17 %. Three parallel strings were used with 66 cells in total. A comparatively low packing factor has been used to eliminate edge shading of the PV cells that may result from the frame of the double glazing.

Figure 4: Glazed nonselective PVT collector at outdoor testing, glazed selective PVT collector at indoor testing.

The glazed solar PVT collector prototypes have been tested under outdoor conditions at the Faculty of Mechanical Engineering, Czech Technical University in Prague, and under conditions of artificial sun at University Centre for Energy Efficient Buildings, Bustehrad (see Figure 4). Tests have been performed in accordance with EN ISO 9806 for the open circuit mode. A mathematical model of the glazed PVT collector was validated and the final collector design was verified.

Figure 5 shows the comparison of the thermal performance characteristics for original glazed PVT collector prototypes (selective, nonselective) and the final design. The comparison has confirmed the excellent properties of the polysiloxane gel encapsulation. The high zero-loss efficiency for the nonselective prototype confirms the good heat transfer from the PV absorber into the heat transfer fluid, and the high transparency of the polysiloxane layer. On the other side, the high radiative heat loss reduces the thermal performance of the nonselective PVT collector at high temperatures. Results for the original selective PVT collector prototype have confirmed the assumption of high reflection losses in the near infrared radiation region due to the low-e coating applied to the absorber laminate glass. Final design has used the low-e coating (emissivity 30 %) with high solar transmittance (86 %).

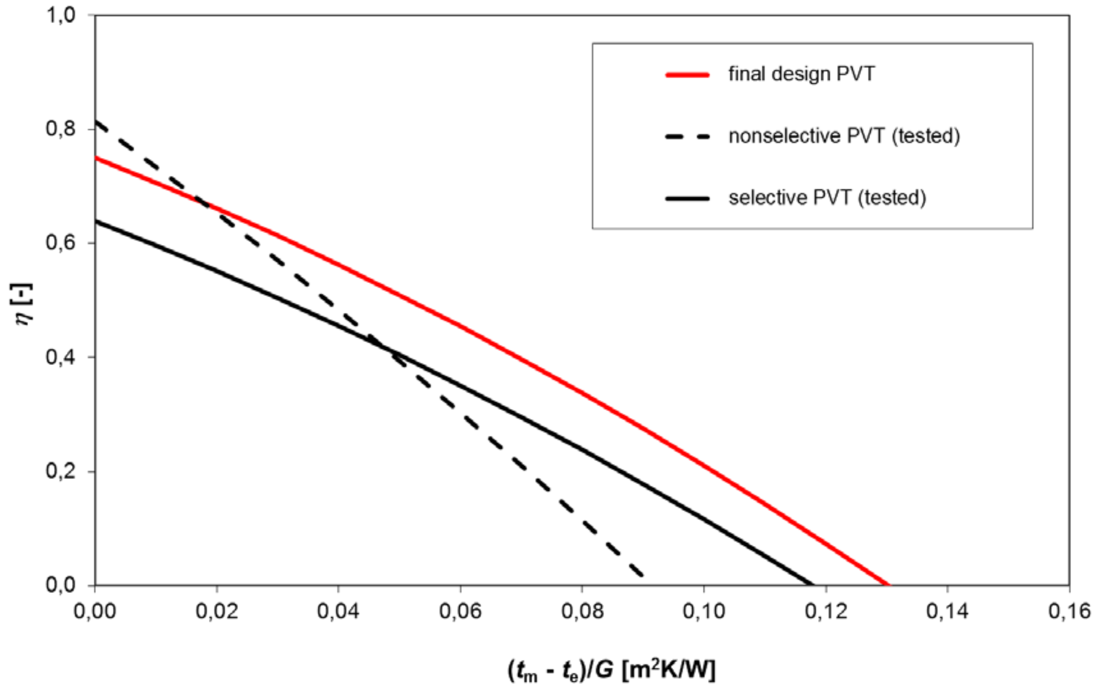


Figure 5: Thermal efficiency characteristics for the developed glazed PVT prototypes (open circuit)

Based on the results for the prototypes, the selective covered PVT collector has been chosen for the MacSheep system. The resulting performance indicators for both modes of operation (with and without electricity use) are shown in Table 1.

Table 1: Performance indicators of the glazed PVT collector (final design).

Model	η_0 [-]	a_1 [W/m²K]	a_2 [W/m²K²]
glazed PVT collector (open circuit)	0,75	4.20	0,012
glazed PVT collector (MPPT)	0,65	3,30	0,012

Since PVT collectors are electric devices, the electric safety has been in the focus from the beginning of the development. Several designs of PV encapsulation with painted copper sheet absorbers have shown to be electrically safe components. The distance between PV cells (and metal contacts) and metal absorber is guaranteed by a glass fiber grid, and the electric resistance is given by the polysiloxane gel. The wiring sleeves through the copper sheet were made from the silicone compound and connected to the junction box at the outer surface of the collector box. The electric resistance was tested by 1 kV applied between the copper absorber and the electric wiring of the PV cells, and a value > 200 MΩ was measured. This result is common for standard PV modules on the market.

Despite that the development of the glazed PVT collector has started within the MacSheep project from level zero, the designed and manufactured product seems to be promising not only for solar and heat pump systems. While other attempts for glazed PVT collector developments failed with the use of the standard EVA encapsulation, the polysiloxane gel compound offers all the necessary features in order to reach both durability and affordability of this new product.

2.2 Advanced heat pumps for solar and heat pump systems

Within the MacSheep project, two brine source heat pumps and one air source heat pump were developed. Two of these developments used the latest generation of variable speed Copeland scroll compressors. In two of the three developments a desuperheater was integrated, and two of the developments used an economizer cycle (vapour injection) in order to cope with low source temperatures such as typically encountered for air source heat pumps and for brine source heat pumps that use uncovered collectors as a heat source.

2.2.1 Brine source heat pump for low temperature source developed by IWT TUG

A brine source heat pump for the use of uncovered collectors as a heat source was developed by IWT TUG. The target heat loads were the SFH45 and SFH100 buildings in the climate of Zurich. The heat pump is equipped with a variable speed compressor, an economizer cycle (vapour injection) and a desuperheater. Two prototypes were built, one with extensive measurement equipment for development, and one compact unit for the final system integration. Figure 6 shows the scheme of the heat pump and typical operating conditions in the temperature-enthalpy diagram.

An existing heat pump model that is based on the thermodynamic properties of the refrigerant in combination with a Bi-cubic curve fit for the compressor performance ($\dot{m}_{ref}$, $P_{el,comp}$ oder η_{is}, η_{vol}) was further developed within the project, validated and used for the simulation of this heat pump with desuperheater, speed control, and economizer cycle.

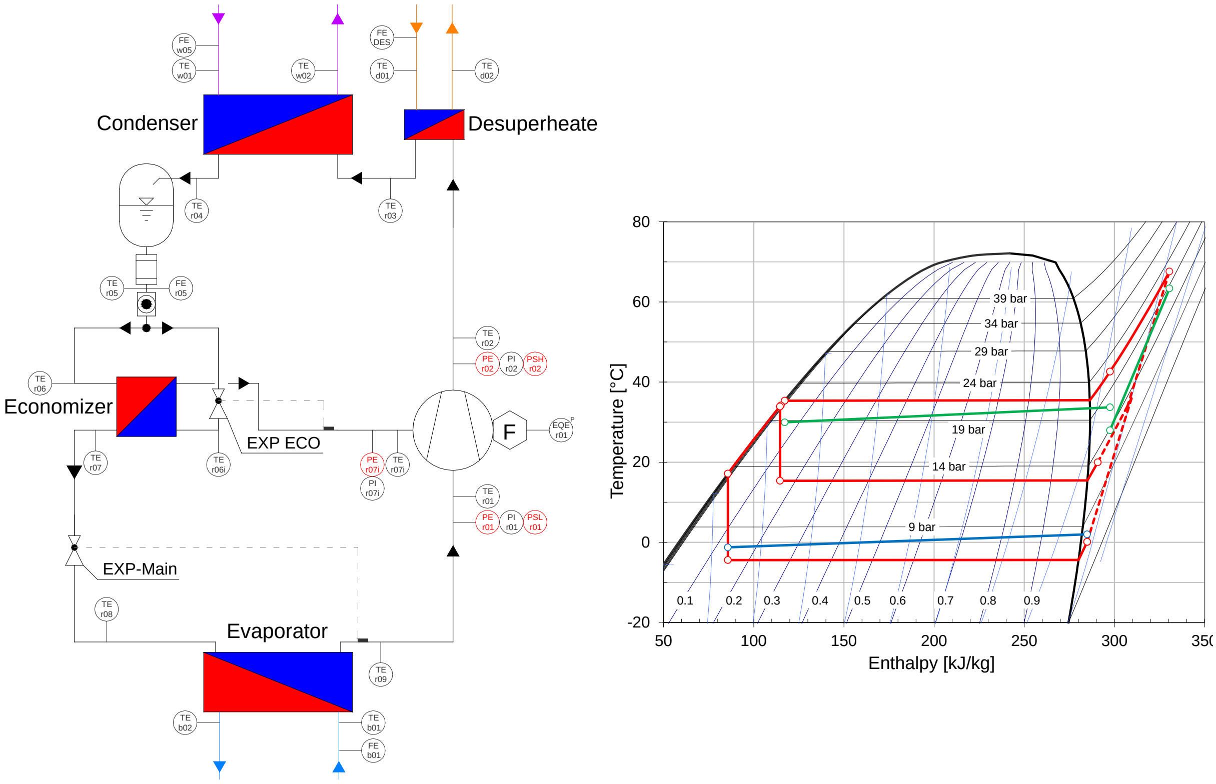
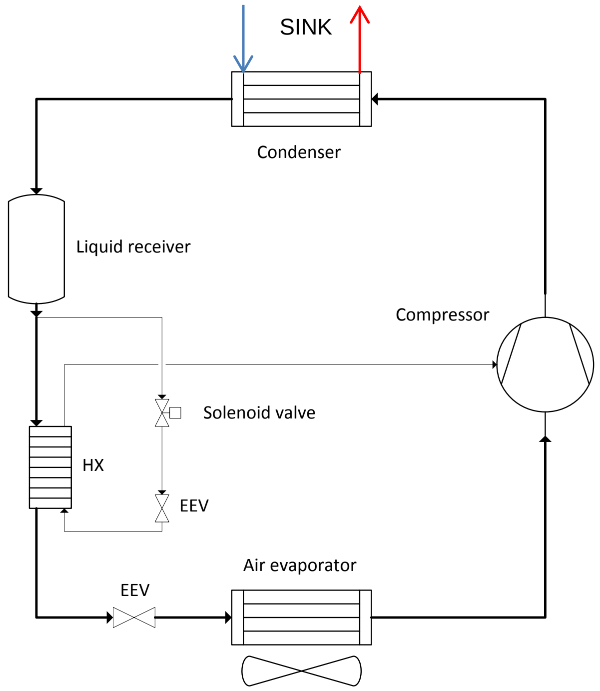


Figure 6: Scheme of the heat pump prototype with its measurement equipment (left) and typical operating conditions in the temperature-enthalpy diagram (right).

2.2.2 Air source heat pump for retrofit buildings by Ratiotherm

At the beginning of phase 3 of the MacSheep project, Ratiotherm developed an innovative cascade heat pump with intermediate temperature level solar heat use. Although the energetic performance of this solution looked promising, the concept was finally abandoned because it was considered too expensive for a market introduction. Instead, Ratiotherm developed an air source heat pump for retrofit buildings (SFH100, supply / return temperatures 55 / 45 °C). This heat pump is equipped with vapour injection in order to achieve a high heating power and COP at low evaporation and high condensation temperatures, using air as a heat source. The outdoor unit was designed by Ratiotherm, functional tests were performed and the heat pump was finally integrated into a full system for testing at CEA INES. Figure 7 shows the scheme of the heat pump circuit and the prototype in the test bench of Ratiotherm.



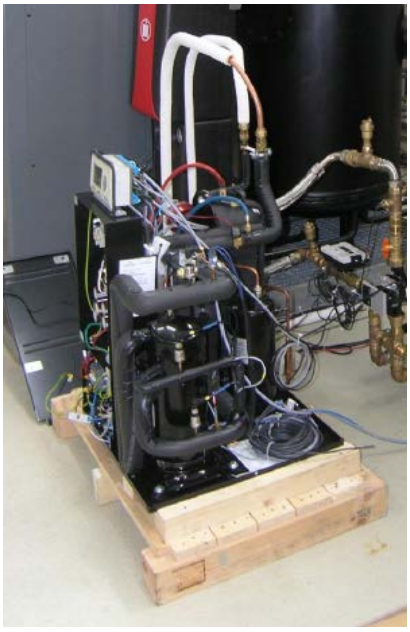


Figure 7: Scheme of the heat pump prototype for retrofit buildings (left) and prototype for testing at Ratiotherm (right).

2.2.3 Ground source heat pump for low energy houses developed by Regulus

A ground source heat pump for low energy houses (SFH45 in Zurich) was developed by Regulus. The original system was equipped with three heat exchangers for heat rejection: a desuperheater, a condenser, and a subcooler. During the course of the project, the subcooler was discarded due to a low benefit for the system performance in combination with solar heat use. Functional tests were made and a heat pump model was developed and validated at CTU Prague. Finally, the prototype was integrated into a full solar and heat pump system for testing at SERC. Figure 8 shows the heat pump cycle together with the prototype unit.

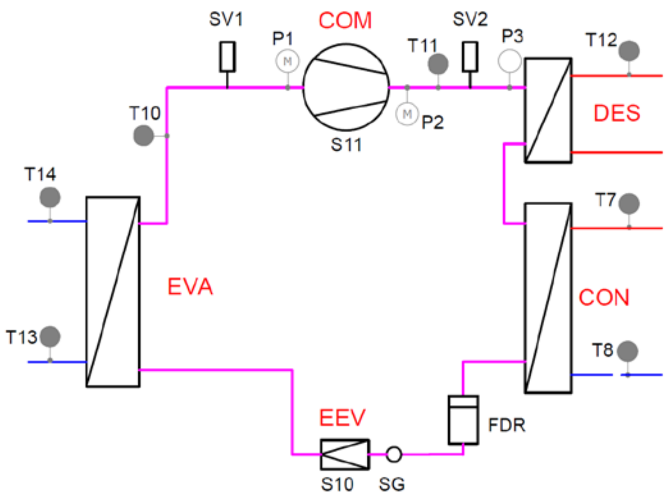


Figure 8: Hydraulic scheme and front view of heat pump that was developed by CTU & Regulus.

2.2.4 Lessons learnt from heat pump developments

The use of a desuperheater for heat pumps with a low capacity posed several problems that had to be solved. First of all, the expected heat output of the desuperheater is quite low. This is even more the case when an economizer is used in the refrigerant cycle, since the economizer causes a reduction of the compressor outlet temperature. The water mass flow rate through the desuperheater must be quite lower than the water mass flow rate of the condenser in order to benefit from high outlet temperatures, and the pipe connections between the desuperheater and the storage tank must be short in order not to lose too much heat in comparison to the small heating power that is transferred. The control of the water mass flow rate through the desuperheater is a challenging task, but a well-working and simple solution has been found for this problem within the project.

The use of a subcooler and the use of solar thermal energy are not well compatible with each other, since both systems compete for the low temperatures for DHW preheating in the lower part of the storage.

In one of the heat pump developments, the control of the speed of the compressor worked as intended. In one case however, the compressor control did not work properly, leading to highly fluctuating compressor speed. This problem was most likely due to electromagnetic compliance issues and could unfortunately not be solved anymore within the project. The establishment of a stable superheating control at the evaporator and the economizer was also challenging, especially in case of a speed controlled compressor with strongly varying refrigerant mass flow rates. For all prototypes stable superheating of only a few K was achieved, enabling an efficient operation under a wide range of operating conditions.

2.3 Advanced storages for solar and heat pump systems

A total of four different storage tanks have been developed for the MacSheep systems.

2.3.1 Tank with internal spiral heat exchanger developed by Regulus

Regulus / CTU have improved the storage tank performance with a clear separation of the DHW part from the rest of the storage (separation plate). Compared to a reference storage tank, it has a larger volume for the DHW zone and a larger surface area of the heat exchanger for DHW preparation has been used in order to reduce the charging set point for the DHW zone. Mixing effects caused by direct inlet ports that are used with high mass flow rates from the heat pump are minimized with the help of inlet diffusors. The heat losses of this 900 liter storage have been determined to 3.3 – 3.6 W/K (60 °C in whole storage), including 8 pieces of connected insulated pipes 1 m long (acting as thermal bridges).

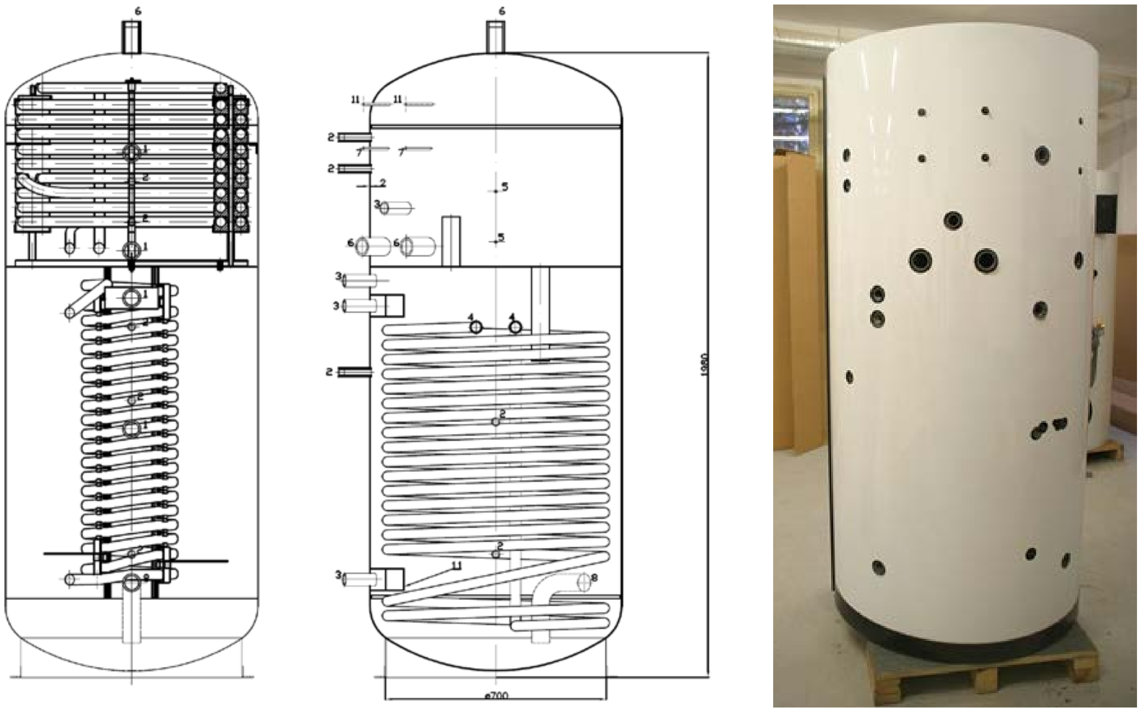


Figure 9: Layout (left) and picture (right) of developed storage tank.

2.3.2 Oscar tank with VIP insulation by Ratiotherm

Ratiotherm has improved the heat losses of their Oscar store with the use of VIP insulation. Thus, it is possible to decrease heat losses to 1.38 kWh/24 h calculated and measured according to DIN 12897. This means the store (920 liters) achieves efficiency class A for the ErP energy label. The store already had a stratifying unit inside the store, together with other measures designed to promote stratification.

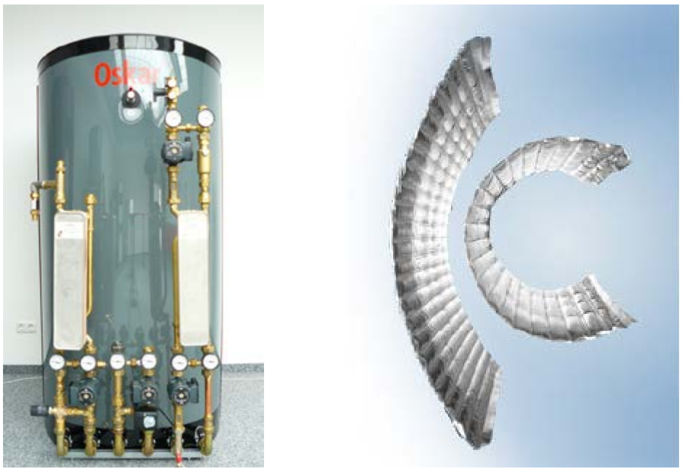


Figure 10: The Oscar storage (left) and new vacuum insulation technology used to reduce the heat losses (right).

2.3.3 Compact heat storage and hydraulic solution with VIP insulation by HSR SPF

HSR SPF have designed a 750 liter storage and heat pump combination that fits under one common insulation as shown in Figure 11. VIPs were used for the insulation shell. However, the joints were tricky to insulate without thermal bridges, and thus heat losses remained at 3.8 kWh/day for the total combination of the storage in combination with the heat pump and the hydraulics. A simple diffusor channel design allows for high heat pump mass flows without increased mixing at the inlet of the storage.

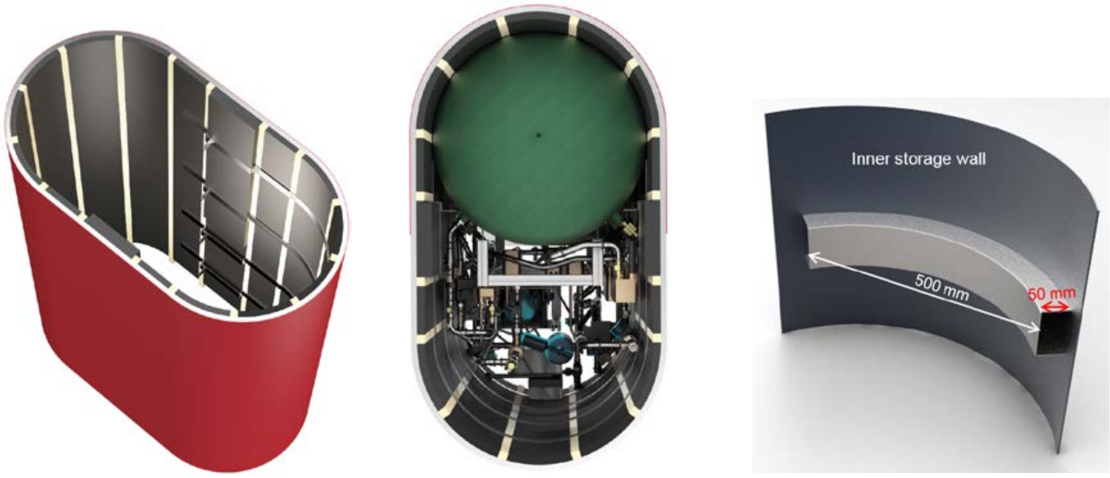


Figure 11: Design concept of the insulation without (left) and with (middle) hydraulic components. The inlete diffusor design is shown at the right.

A new plug flow storage simulation model was developed. In comparison to the conventional fixed volume / fixed node simulation models, the new model is less biased by numerical diffusion which is an advantage for the simulation of stratification effects.

2.3.4 Storage with integrated heat pump condenser by Viessmann & CEA INES

CEA INES and Viessmann developed a storage tank with integrated heat pump condenser. A first prototype of an internal heat pump condenser achieved overall heat transfer coefficients of 320 W/(m^{2}K) on a surface of 1 m^2. It was found that the pipe inside diameter had a large influence on the heat transfer coefficient. In order to increase this value to 600 W/(m^{2}K), a smaller diameter and a larger total surface have been chosen for the final product. Viessmann also developed a new heat trap design in order to reduce heat losses in standby. The heat losses of the storage are 2.9 kWh/day (whole storage 60 °C).

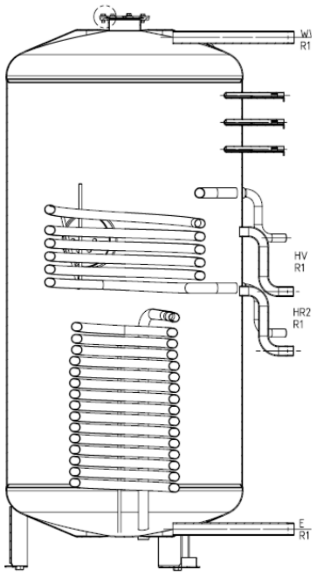


Figure 12: Storage with integrated heat pump condenser built by Viessmann & CEA INES.

2.3.5 General lessons learnt from storage developments

It was found that the storage design and management has a much larger influence on the overall performance of systems with heat pumps than most experts and developers expected. The storage tank and its proper integration into the system clearly are key elements for an efficient system design. In particular, storage tank stratification and the exergetic efficiency of the overall storage process are of utmost importance, and much more important than reducing heat losses to the level of ErP Energy labels A or B. Therefore, effort has been invested in improving storage tank stratification and achieving a good separation between the DHW zone and the space heating zone.

Keeping the temperature level of the DHW zone as low as possible, but at the same time high enough to guarantee the required comfort, is another key element. Thus, the design of internal and external heat exchangers for DHW and the control of external DHW heat exchangers are also key elements for efficient design of solar and heat pump systems.

2.4 Advanced control for solar and heat pump systems

Advanced control features were analyzed and developed within the MacSheep project. Among the investigated concepts were:

- ***Model predictive control*** that enables the use of the building thermal mass to store heat when solar energy is readily available or when heat pump operation is favourable. However, the robustness of such control algorithms for solar and heat pump systems could not be sufficiently assured and thus these algorithms were not yet implemented in products.
- ***Self-learning algorithms*** for DHW consumption forecast that enables to reduce the set point for DHW when no DHW consumption or only little DHW consumption is expected. This approach showed to be interesting both from an efficiency and from a cost-effectiveness persepective and has been implemented by Viessmann. Figure 13 shows the result of a pattern detection algorithm that does not rely on information from the external DHW module control.

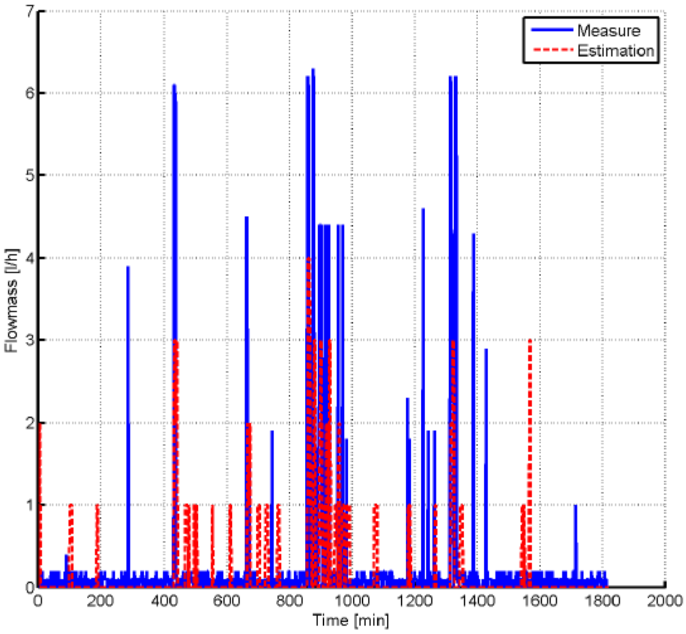


Figure 13 DHW tapping detection (estimation) based on storage tank temperatures developed by Viessmann.

- ***Electricity price forecasting*** that allows for a minimization of electricity cost was analyzed by SERC and showed promising results. However, the reality of the market and the non-generic character of the solver has not allowed for an implementation of this algorithm in a controller prototype yet.
- ***Fault detection:*** The method developed in MacSheep for the detection of reversal of supply and return lines of the collector loop has been implemented in the current auxiliary burner Vitodens 300W launched on the market in the first quarter 2015. This failure is a frequent commissioning error. As a result of the MacSheep project, the controller of the Regulus heat pump is able to ***detect more than 20 common faults*** that can occur in the heat pump circuit or in the connected hydraulic loops. A fault information display of the system is shown in Figure 16.
- ***ICT communication and control has been implemented both at Viessmann and at Regulus.*** The new Vitotrol app launched in the beginning of the year 2015 allows the users

to remotely operate a Viessmann heating system with Vitotronic controls. The operation of the app is simple, easy and comfortable to use from anywhere and at any time of the day. The application offers context specific help accessible through the GUI. The Viessmann Vitotrol app will provide access to the following features of the Vitotronic heating controller. In the future, this app may allow for additional functionalities such as visualization of DHW tapping profile and functions to remotely express DHW need respecting current charge state of the system. Exemplary screens are depicted in following Figure 14.

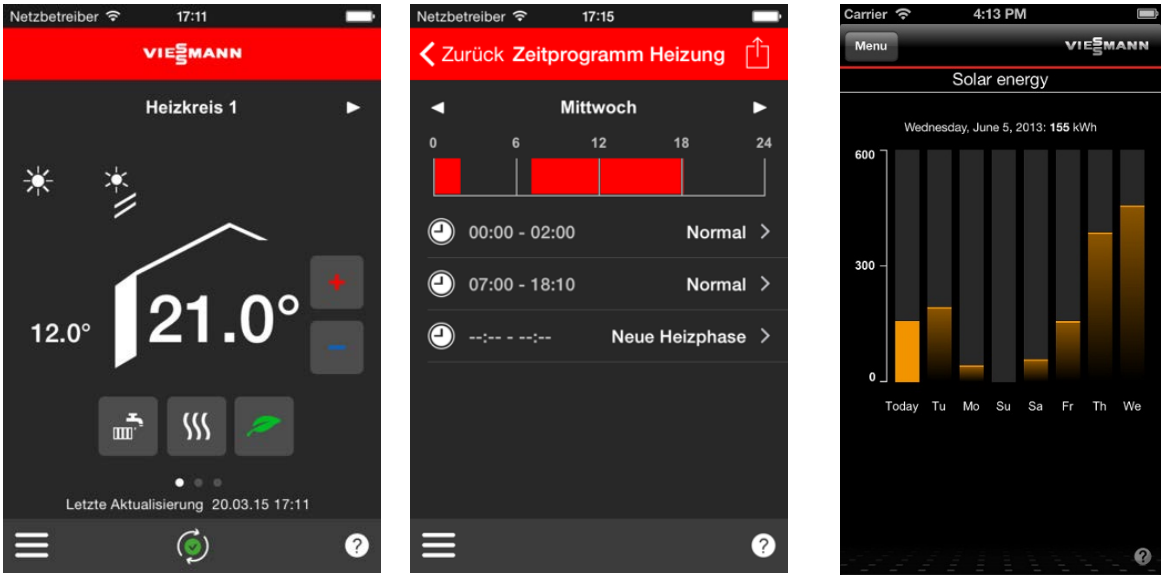


Figure 14 Example screen of Vitotrol Plus App.

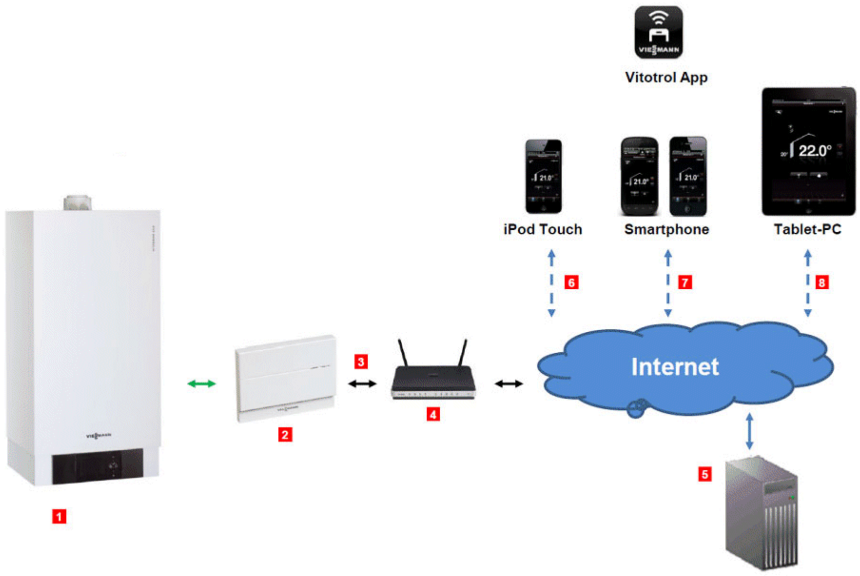


Figure 15 System configuration: [1] Heating device with communication module [4] DSL-Router [5] Vitodata Server [6] WLAN-Connection [7] WLAN-Connection or mobile network [8] WLAN-Connection or mobile network.

Figure 16 Fault detection warning display for the Regulus controller.

2.5 Improved and accelerated whole system test methods

When the project started in 2012, the research and test institutes CEA INES in France, SERC in Sweden, and HSR SPF in Switzerland were already performing whole system tests that followed similar, but yet different, methodologies (see Haller et al. 2013). These institutes developed a harmonized and improved test method within the MacSheep project. The full description of the test method is reported in Del. 2.4 (Haberl et al. 2014), and a shorter description is presented in Chèze et al. (2014).

2.5.1 Main steps of harmonization and improvements

The main harmonization steps and improvements within the MacSheep project were:

- The different ***system boundaries*** for testing that were reported in Haller et al. (2014) have been ***harmonized*** to the system boundaries shown in Figure 17.
- The ***boundary conditions for climate, domestic hot water (DHW) draw-off and space heating (SH) demand*** were revised, harmonized, and based on publicly available models and data. A new building model was implemented in TRNSYS according to standard EN ISO 13790:2008. The set of parameters for this new model was defined for SFH45 and SFH100 of the IEA SHC Task 44 (Dott et al. 2013), which gives a heat load of 60 kWh/(m^{2}a) for the SFH45 if placed in the chosen reference climate of Zürich.
- The 12 days test sequences and the six day sequence that were used in the three institutes before the MacSheep project were replaced with a ***new 6 days test sequence*** (Figure 18) that has been validated for the **direct extrapolation of results to annual values** from the six day values for the case of solar thermal and heat pump systems.
- One of the most important improvements of the method within the MacSheep project was achieved by finding a ***solution for the space heat load emulation that leads to identical amounts of heat delivered to the space heating for different systems on the same test day, while still including a quite realistic behavior of the space heat distribution***.
- A ***common procedure was defined for the DHW tappings***. This procedure takes into account the fact that higher supply temperatures for DHW will cause the user to mix more cold water to the hot water at the tap in order to reach his desired temperature. Thus, the mass flow rate of the hot water line is reducing with increasing temperatures of the supply. A common procedure and hardware requirements have been defined and implemented in order to emulate these effects.
- The six day test sequence is designed as a test cycle that can be repeated over and over again, always leading to the same result. A "***concise cycle***" is achieved if the heat and electricity transfer measured at the system boundary is nearly identical for two days with the same "ID", i.e. for a day that is already running for the second time because of the cycling nature of the test procedure. If this criteria is met it can be assumed that the energy stored in the system at the start and at the end of the corresponding cycle is identical. Thus, it is not necessary to know the exact energy content of the system at the beginning at the end of the test and to determine a difference in energy content, since it is enough to know that the energy content is almost identical and differences are negligible.

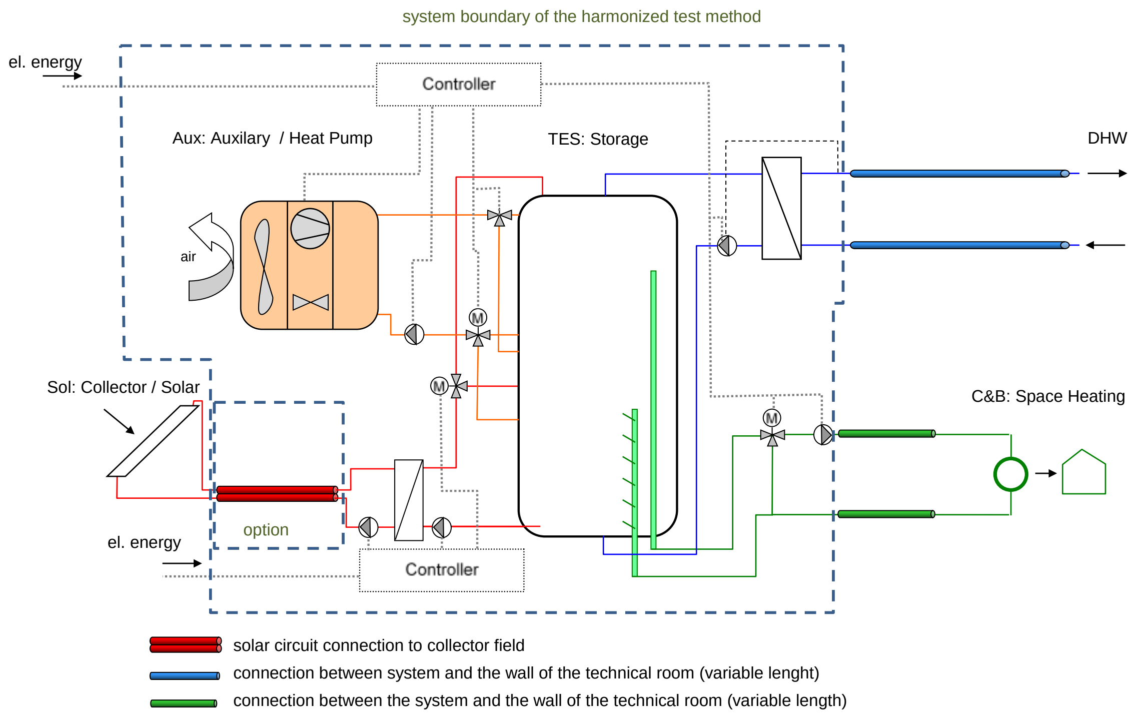


Figure 17: Simplified hydraulic scheme showing the system boundaries where the energy balances are measured.

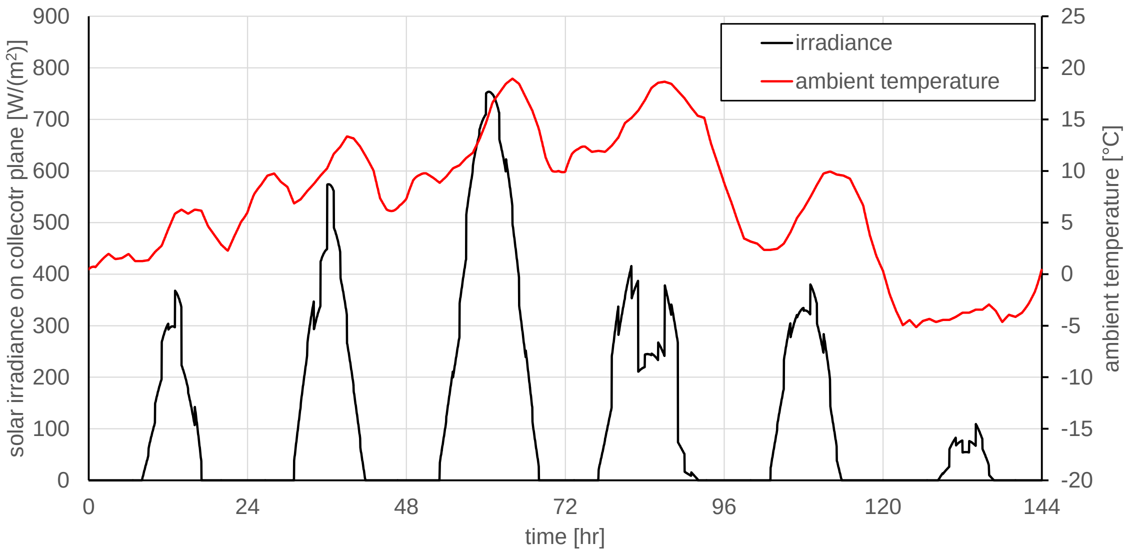


Figure 18: The ambient temperature and solar irradiance on the collector plane for the 6-day test sequence.

2.5.2 Lessons learnt

The new harmonized whole system test method was applied successfully within the MacSheep project. In particular:

- The harmonized physical boundaries were applied by all test institutes and found to be logical and consistent.

- The method to achieve identical heat loads for space heating was successfully demonstrated. This is an important feature for the test method to qualify as a benchmark test.
- The six day test sequence based on Meteonorm data with a resolution of 1 hour has been used successfully, and is considered to be sufficient for most applications, in particular for solar thermal and heat pump combination. However, this aspect has to be looked at again for other systems in the future, e.g. for PV self-consumption heat pump systems.
- A harmonized DHW profile and tapping procedures were applied by all three test institutes.
- The direct extrapolation of the test results leads to a massive reduction of the effort of system testing and evaluation. The reason for this is that the fitting of simulation models for the determination of annual results and for the validation of the direct extrapolation of test results to annual values – although still practiced in MacSheep for the reasons explained in Del. 8.3 – can be spared in the future.
- The concise cycle approach with the criteria of near to equal results for two days with the same ID after having gone through the whole cycle of days proved to be a reliable and well-functioning approach for this kind of test.

Finally, and most importantly, the determination of a benchmark result for the performance of a system for the supply of space heating and domestic hot water was successful. In particular, the difference between the annual key performance figures determined based on direct extrapolation of the whole system test results and annual figures derived from calibrated annual simulation results were low (5-8 %), despite the fact that the systems included features (direct PV use, series collector heat use) for which the method was not previously validated.

Furthermore, whole system testing revealed many problems of system control, installation, mal-functions, and non-optimal hydraulics and temperature sensor placements. Thus, for system development as well as for performance characterization, the whole system test method shows significant advantages over any approach that is based on component testing only, while at the same time being less time consuming and more straightforward.

Work that still needs to be done in further projects are:

- Dealing with methods for the extrapolation to other heat loads
- Inclusion of methods for the consideration of time-synchronous on-site PV electricity supply to the heating system (PV heat pump or PV electric heating systems)
- Checking the influence of the time resolution of weather data on the determination of PV electric self-consumption
- Refining the application of penalty functions for not meeting DHW comfort temperatures
- Defining a simple heat transfer and heat capacitance calculation model for the heat emitter simulation (radiator / floor heating) and emulation in the test bench.

Further work might also include additional test sequences for the determination of the DHW discharge volume, as well as a short test cycle for the determination of heat losses with reduced uncertainty (less turnover of energy compared to the amount of heat losses).

2.6 Overall system concepts and performance

The main goal of the MacSheep project was the development of solar and heat pump systems that would perform 25 % better in terms of electric energy demand, compared to a state of the art benchmark solar and heat pump systems, while still being competitive in terms of prices for the end-consumer.

The key performance figures that were evaluated were thus the annual electricity consumption of the entire system for a given heat demand profile, and the annual system price that includes installation, maintenance, and electric energy purchase.

In order to be able to calculate electrical savings, benchmark systems were selected and measured with whole system test methods in the test bench both for a ground source and for an air source solar and heat pump system. Simulations were calibrated with the results of whole system testing. It should be noted that the state of the art benchmark systems that were tested in phase 2 of the project did not reach the expected performance. Thus, "easy to fix" problems of design, installation and operation were fixed in the annual simulations of the benchmark systems in order to reach a better performance that would correspond more to what we would expect from a well-designed and fault-free installed state of the art system. These improvements included:

- Hydraulic integration of the combi-storage and placement of the DHW temperature sensor according to the recommendations that have since been published by HSR SPF (www.spf.ch/sol-heap).
- Reduction of mixing effects in the storage that were caused by high mass flows of heat pump inlets.
- Reduction of heat losses that were caused by natural circulation through pipings for DHW and cold water supply outside of the storage.
- Correction of storage design that prevented the preheating of DHW by solar in the bottom part of the store.

These improved benchmark systems performed about 20 % better (i.e. 20 % less electric energy use) than their truly installed and tested counterparts.

The four systems that were developed within MacSheep had different heat load targets for which they were optimized. Obviously, optimization for a high heat load and high supply temperatures of the heating system can lead to a quite different solution than optimization for low heat loads or low temperature heating systems. When there is not much heat to deliver in the first place, increasing energy efficiency must only be achieved by low cost solutions since the same percentage of electrical savings is much less in absolute terms of electricity cost than for a system with a high heat load. Such considerations also lead to quite different approaches for the four developed systems.

The final results that are based on whole system testing for three of the four systems, and on component testing and system simulation for the fourth system, show that two of the four systems are able to meet or pass the target of 25 % electricity savings for the load and climate for which they were optimized. Another system reached close with 24 % and good potential to increase to 26 % with further simulated improvements made. The fourth system reached 15 % savings, which is still a very good value considering also that in this fourth case a first route of development with an already built prototype had to be abandoned during the project, and less time was then available for the development of a new system.

If these savings would be based on a comparison with the “not improved” state of the art benchmark systems as they were measured in the test bench, the improvements would be even higher. For example, for the cases of the ASZ45 and the GSZ45 heat loads, a system that is reported with 25% savings would save 40 % of electric energy if compared to the “not improved” benchmark systems, i.e. if compared to a system that is likely to correspond to an average solar and heat pump installation today.

Table 2: Overview of percent electric savings and annual cost savings for the respective main target heat load for the four developed MacSheep systems.

system	**target heat load**	**electric energy savings**	**cost savings per year**
System performance evaluation based on whole system testing and system simulation			
ESSA, IWT TUG & HSR SPF	ASZ45	24 %	59 €
Ratiotherm, SERC	ASZ100	15 %	82 €
Regulus, CTU	GSZ45	26 %	13 €
System performance evaluation based on component testing and system simulation			
Viessmann, CEA INES	ASC45	30 %	136 €

AS = air source, GS = ground source, Z = Zürich, C = Carcassonne, 45 / 100 = space heat load in kWh/(m^{2}a) if placed in the climate of Strasbourg.

Two of the developed systems, the one from Regulus-CTU and the one from Viessmann & CEA INES, have implemented fault detection and smart control algorithms. The benefits of these control features could not be tested or evaluated with the whole system test method. In reality, these control features would bring additional electric savings for installed systems during their operational lifetime. These added savings have not been quantified or shown.

3 Impact

3.1 General impact

The following ***topics of the work programme***[2] were addressed by the ***MacSheep project***:

- improve performance, ease of use and penetration of solar thermal systems
- making use of breakthroughs in scientific and technological fields, including novel materials and ICT, in an integrated manner
- deliver low cost, high efficiency, reliable and intelligent solar thermal systems
- characterisation and test methods
- competitive costs
- enhanced functionality
- limiting of temperatures during stagnation
- active participation of industrial partners, especially SMEs

The overall objective of the MacSheep project was to develop a new generation of combined **S**olar and **h**eat pump systems with boosted **e**nergetic and **e**xergetic **p**erformance, ***implementing new Materials and smart control strategies that make use of ICT***. The combination of solar thermal energy with heat pumps is a combination of two ***low-carbon technologies***. The carbon footprint of a solar thermal collector is extremely low and depends only on the carbon-intensity of its production, installation and disposal or recycling, with no significant impact from its operation. The carbon footprint of the heat pump additionally depends to a large extent also on the electricity generation system that supplies the electricity needed to run the heat pump. Thus, in order to reduce the needed amount of sustainable electricity production, ***it is essential to reduce the electricity consumption of the entire solar and heat pump system to a minimum***. This minimal electricity demand will in the future be supplied by a wide range of sources through smart energy grids, with an increasing share of renewables and a decreasing carbon footprint, according to the EU commissions "A Roadmap for moving to a competitive low carbon economy in 2050" (EU, 2011).

The MacSheep systems reach a ***performance improvement of 25% or more in terms of energy savings*** compared to the state of the art for combined solar and heat pump systems at the beginning of the project, with still ***competitive prices*** on the market for the complete system installed in the building. Combined systems, with two or more heat sources and two or more heat loads, are relatively complex and thus require robust and advanced controllers. The impact of the systems in a life cycle perspective is dependent on the optimal functioning over their whole lifetime. For this purpose, the MacSheep project adds ***enhanced functionality*** to solar thermal systems with ***automatic failure detection and intelligent control*** based on user and load predictions and ***ICT***. New breakthroughs in the development of solar collectors included ***selective paints for metal collectors*** that ***reduce costs*** as well as hybrid air-source / solar-source and photovoltaic/thermal-collectors. ***Innovative compact storage solutions*** were built with storage integrated heat pump units, improved stratification, and reduced heat losses.

One of the main results of the project is a ***harmonized test method for whole system testing*** that has several impacts. Firstly it will be possible to use in the future for consumer tests of products and even certification, with a ***significant impact on information to the market***. Secondly the method has an impact by ***reducing development times for future combined***

[2] FP7-ENERGY-2011-1 – Cooperation Theme 5 – ENERGY.2011.4.1-1

renewable energy systems. Complex systems with a high degree of integration and advanced control require methods that can test the operation of the whole system over the complete range of targeted operating conditions. The method will accelerate this process by ***reducing the need for time consuming and expensive field testing*** and thus reduces overall development time. A third impact is that there are now several test institutes from different countries with detailed knowledge and experience in the method, that can help SME's with their future development of systems.

The combined solar and heat pump systems developed and improved in the MacSheep project will be an important part of the ***mix that will supply 100% renewable energy to the building sector***. An important aspect is seen in the fact that the developed systems are not only suitable for new buildings for which a low heat demand is already required by national laws and EU directives, but also to ***renovation objects*** or objects with limited possibilities for thermal insulation, thus speeding up the reduction of non-renewable energy use in a sector where it is difficult to reduce the energetic demand by other means, or where „waiting" for the next renovation or destruction could jeopardize the goals set for the ***reduction of greenhouse gas emissions***. Single family households account for more than 50% of the dwellings within the EU15 (Federcasa 2006, p. 56). For these houses, ***compact pre-fabricated combined solar and heat pump units*** have a large potential. However, the project results will also be important for subsequent adaption and up scaling of these systems for multifamily houses. ***The developments and lessons learnt from the MacSheep project will thus have a large impact on the whole domestic building stock, current and future, new buildings as well as retrofit.***

For example, if a share of 50% of the low temperature heating demand of the EU27 will be produced with heat pumps by 2030, the consequent application of MacSheep system technology will ***save electricity in the order of the annual production of 33 nuclear power blocks of 1 GW electric capacity each***[3]. Of these 33 GW_{el}, 19 GW_{el} can be attributed to the combination with solar energy alone, and an additional 14 GW_{el} to the specific application of MacSheep technology that saves an additional 25% of electricity. The equivalent in CO_2 emissions that would arise from an electricity production in coal fired power plants is estimated as ***289 Mt CO_2-eq per year***[4]. Of this figure 165 Mt CO_2-eq/a can be attributed to the application of solar thermal technology alone, and 124 Mt CO_2-eq/a to the additional savings due to MacSheep technology. These figures correspond to **6.4%**[5] (3.7%+2.7%) **of the estimated current greenhouse gas emissions of the EU27**.

[3] Assumptions: Low temperature heat demand of the EU 27 for 2030: 320 Mtoe (RHC 2010, "Full Research, Development and Policy Scenario"); 42 GJ/Mtoe; average Seasonal Performance Factor of the heat pumps without solar 3.5; 25% savings by combination with „ordinary" solar thermal systems; additional 25% electricity reduction by MacSheep technology; nuclear power block available 90% of the year; transmission and conversion losses for electricity produced: 10%.
[4] Assumptions: CO_2 emissions of electricity over the grid from coal fired power plants: 0.344 kg CO_2-eq./MJ_{el} (Frischknecht & Tuchschmid 2008).
[5] Current emissions are assumed to be 4 500 Mt CO_2-eq./a (EEA, 2010, p. 11)

3.2 The way to market for specific MacSheep developments

- **Viessmann Faulquemont:** Some of the MacSheep developments are now already on the market, i.e. implemented in the Vitotronic 200 control. Also the heat traps which were developed in the MacSheep project are already implemented, and the lessons learnt from storage stratification and hydraulic integration influenced storage products like Vitodens 300. The storage integrated condenser that was developed within the MacSheep project has not been introduced to the market yet. Further development is still needed in order to bring this breakthrough to the market too.
- **Ratiotherm:** Ratiotherm will test the heat pump further to solve remaining control problems with the Copeland compressor. Then, the existing heat pump system will be re-designed, combining different developments of the whole MacSheep project. The time window for a new system is spring 2016, this system should include a number of developments from the MacSheep project.
- **ESSA:** The new absorber developed during the project is used already for some collectors. A new ERA-NET MANUNET project "BiSolar" is just starting were the durability of this new coating will be investigated further in collaboration with HSR SPF and the University of Brasov (Romania). Furthermore, the development of ice storages that can be combined with the ESSA system is further investigated in a national project between HSR SPF and ESSA that is financed by the Swiss Commission for Technology and Innovation (CTI).
- **HSR SPF / IWT TUG:** The compact storage and heat pump combination with desuperheater, speed control and vapor injection will finally not be built by ESSA. HSR SPF / IWT TUG are in contact with two manufacturers that are interested in further investing in this technology. A transfer of the laboratory control hardware and software to industrial controllers is needed, and further improvements of the insulation, the desuperheater, and the DHW heat exchanger and control will be the topic of a follow-up project for which financing will be applied for in the first half of 2016.
- **Regulus:** The improvements in storage stratification and control with remote access and fault detection are already implemented into the new products of Regulus today. Due to the current market situation in Czech Republic (compared to the time of the project start), the heat pump and PV-heat pump combination will not yet be introduced to the market. However, Regulus is continuing to work together with CTU in order to develop a PV and heat pump system that is making use of the MacSheep developments.
- **CTU:** The PVT collector development is very promising. Some more time has to be invested for testing and certification of the module. After that CTU will look for a manufacturer via European Enterprise Network. It is a clear strategy of CTU to bring the PVT collector into the market. A challenge is how to deal with the license of the encapsulation of the PV-cells, because the license is not owned by CTU.

Finally, concerning market penetration, two market developments have to be mentioned that have changed the situation compared to the beginning of the project:

- The extremely ***low oil price*** (around one fourth compared to 2008) has led to a decrease in heat pump sales and in solar thermal sales over the past years, and continues to be a large challenge for market penetration of renewable energy systems in general.
- Many countries have implemented quite important ***subsidy schemes for photovoltaics*** on single family homes, and the ***price for photovoltaic systems*** has decreased substantially. For this reason, solar thermal and heat pump combinations are today in a strong competition with the new emerging combination of photovoltaics and heat pump. These new systems that combine photovoltaics with heat pumps in order to cover a large

share of heat pump electricity consumption by on-site produced photovoltaics will certainly take a share of what was thought to be the market potential for solar thermal and heat pump systems. The challenge here is to increase the self-consumption of photovoltaics by a control of the heat pump that will produce heat not only when heat is needed, but also when photovoltaic energy is available. Thus, thermal storage is a key component also for these systems. Luckily, most of the developments made within the MacSheep project are also compatible with PV and heat pump systems. This is particularly the case for covered PVT collectors, combi-storages with enhanced stratification capabilities and reduced heat losses, heat pumps with desuperheater, speed control, and / or economizer cycle, storage integrated heat pump condenser, automatic fault detection, DHW demand forecast, and ICT for remote control and supervision. Part of further work might thus also include further development of MacSheep systems for the use of PV and heat pump combinations.

3.3 Messages for decision makers

The term “solar and heat pump systems” may be used for combinations of heat pumps with solar thermal systems, PV systems, or PVT systems. Solar and heat pump systems have a large potential for reducing the carbon footprint and non-renewable energy use of our building stock. They might even be the main provider of heat for buildings in 2050, and the possibility to use these systems also for cooling will increase their attractiveness further. For this reason, more attention should be given to these systems, their improvements, and means for creating incentives for end-consumers to buy these systems in order to create a fully commercial market segment.

The results of the MacSheep project show that efficient systems are more than just adding together efficient components. This is particularly the case for solar and heat pump combinations where details or system integration and control have a decisive influence on the overall system performance. Significant energetic savings are not guaranteed with the combination of energetic efficient components only. The overall system design and control is much more decisive for a good result. For this reason, the evaluation of system performance should be done based on on-site energy metering and supervision, or based on whole system tests using realistic operating conditions.

For the case of thermal combi-storage devices in combination with heat pumps, the thermal storage stratification and the exergetic efficiency of the storage process showed to be much more important than the reduction of heat losses. For this reason, also energy labelling schemes like the ErP should be improved for taking into account stratification efficiency and exergetic performance of thermal storage, and not just thermal losses.

Heat losses of combi-storages are currently evaluated at a temperature difference of 45 °C to the ambient, similar as for a DHW tank. Whereas this temperature difference represents a normal use-case for a DHW tank, it is not a representative temperature difference for the operation of a combi-storage. Due to the different zones of the combi-storage, this device will have a much lower temperature difference in the bottom where domestic hot water is preheated by solar energy, and in the middle that is kept at the temperatures of the space heat distribution for most of the year. Therefore, a fair determination of heat losses of solar combi-storage devices should be done based on a test-procedure that evaluates heat losses under these true operating conditions.

4 Website and contact details

More information can be downloaded from the website:

www.macsheep.spf.ch

All public deliverables and published conference contributions as well as AAM versions of peer reviewed articles can be downloaded from this website.

Until 2016, the Website has registered over 2'000 visitors, and more than 500 downloads.

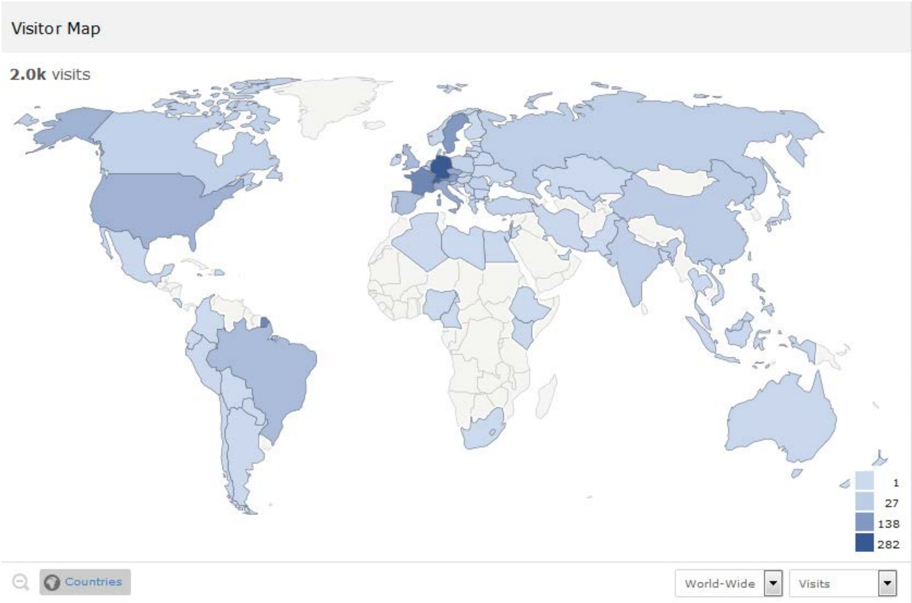


Figure 19: Origin of website visitors.

The organizations involved in the MacSheep project were:

Coordinator and research partner

- Institut für Solartechnik SPF of the University of Applied Sciences Rapperswil (HSR) www.spf.ch

Other research partners

- Solar Energy Research Center of Högskolan Dalarna (SERC) www.du.se
- French National Institute for Solar Energy (CEA INES) www.liten.cea.fr
- Department of Environmental Engineering of the Czech Technical University Prague (CTU Prague) www.cvut.cz
- Institute of Thermal Engineering of Graz University of Technology (IWT TUG) www.iwt.tugraz.at

Small and medium enterprises

- REGULUS spol. s.r.o.
  www.regulus.eu
- Ratiotherm Heizung+Solartechnik GmbH & Co. KG
  www.ratiotherm.de
- Energie Solaire SA (ESSA)
  www.energie-solaire.com

International industrial

- VIESSMANN Faulquemont S.A.S.
  www.viessmann.com

5 Symbols and Nomenclature

A	Air source
C	Carcassonne
CEA INES	Center for Atomic-Alternative Energy - French National Institute for Solar Energy
COP	coefficient of performance
CTU	Czech Technical University in Prague, Faculty of Mechanical Engineering
DHW	domestic hot water
ESSA	Energie Solaire SA
G	Ground source
HSR SPF	University of Applied Sciences Rapperswil, Institute for Solar Technology SPF
IEA	International Energy Agency
IWT TUG	Institute of Thermal Engineering, Graz University of Technology
PV	photovoltaic
PVT	photovoltaic thermal collector or absorber
SERC	Solar Energy Research Center of Högskolan Dalarna
SFH	single family home
SFH100	SFH with 100 kWh/(m^2a) heating demand if placed in the climate of Strasbourg
SFH45	SFH with 45 kWh/(m^2a) heating demand if placed in the climate of Strasbourg
SH	space heating
SHC	Solar Heating and Cooling
SPF	seasonal performance factor (or SPF Institut für Solartechnik)
VIP	vacuum insulation panel
Z	Zürich