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Solar-thermal Systems Based on Polymeric Materials:
Novel Pumped and Non-Pumped Collector-Systems

SolPol-4/5

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Solar-thermal Systems Based on Polymeric Materials

Novel Pumped and Non-Pumped Collector-Systems

SolPol-4/5

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2 Introduction and Brief Description of the Project

Solar-thermal collector systems are currently produced in rather cost-intensive manufacturing processes utilizing a variety of different mostly non-plastics materials. While the world market for non-pumped solar-thermal systems (thermosiphon systems and integrated storage collectors) continuously exhibited extraordinary growth rates over the last ten years, the European solar-thermal market, which is dominated by pumped flat-plate collector systems, was found to stagnate or even shrink over the last years.

Hence, the overall objective at the outset of the present project *SolPol-4/5* was to develop market-competitive pumped and non-pumped solar-thermal systems in an all-plastics or a hybrid-material design. These novel systems should exhibit the following key-characteristics:

- high degree of pre-manufactured components and optimized function integration,
- reduced collector weight and ease of installation (plug&function),
- high reliability and long lifetime,
- attractive design and appearance, and
- reduced costs/prices for end-consumers as well as an improved cost/performance ratio and improved eco-efficiency.

In terms of economic and ecological goals the project strives to contribute towards re-stimulating the European and Austrian market deployment for solar-thermal hot water supply and for space heating, while simultaneously significantly reducing greenhouse gas emissions. Furthermore, and simultaneously, the position and competitiveness of Austrian solar-thermal companies should be significantly strengthened.

More specifically, by applying a science-driven approach guided by and based upon strong industrial-technological experience, the project pursued the following 2 major goals:

(1) To conceptually develop, practically build, function-proof and evaluate highly polymer based, pumped collector model systems achieving systems costs reductions by about 50 % compared to current systems.

(2) To develop novel non-pumped, integrated storage collector (ISC) systems in an all-polymeric or a hybrid-material design that combines the attributes of high comfort and high quality/reliability with low-to-moderate costs.

Project Goals and Deliverables

Based on the above description of the state of technology, the overall objectives, and the major problems to be resolved, *SolPol-4/5* pursued the following specific **technical, economic and scientific goals**:

(1) To conceptually develop, practically build, function-proof and evaluate highly polymer based, pumped collector model systems for domestic hot water (DHW) and space heating (SH) applications in Europe and North America achieving systems costs reductions by about 50 % (i.e., ~500 €/m^2) compared to current systems while offering an equivalent lifetime of at least 20 years.

(2) To develop novel non-pumped, integrated storage collector systems in an all-polymeric or hybrid design for DHW preparation in sub-tropical and tropical climates, that combine the attributes of high comfort and high quality/reliability with low-to-moderate costs of about 500 to 700 € for a collector system with 2 m^2 of collector area and 150 l storage volume along with a guaranteed lifetime of 10 years, and a reduction of the overall mass below 70 kg for ease of transport and installation.
(3) To define a catalogue of required performance profiles for polymeric materials for various collector system designs and climate regions on the level of individual components, to aid material selection and to guide material development efforts throughout the course of the project but also beyond.
(4) To develop novel polymer compounds and semi-finished product types, tailored towards specific applications in various components of pumped and non-pumped systems.
(5) To develop and implement a portfolio of test methods that allow for efficient and reliable material screening and ranking, and for material qualification and durability assessment under various superimposed mechanical, thermal, environmental loading conditions.

Most of the pumped solar-thermal systems built even today are installed at the application site in a great variety of systems designs, using collectors provided by solar-thermal collector manufacturers and other components being provided by a large number of different vendors. This not only is a key reason for the high share of installation costs on the total systems costs, it frequently also is the cause of non-optimal systems operation and deficiencies. Hence, referring to the above project goal (1), a key issue in reducing overall systems costs of pumped solar-thermal systems while simultaneously improving reliability and performance was to develop more standardized systems and systems components with a high degree of prefabrication and function integration, thereby simplifying solar-thermal systems installation on site by means which may best be described as “plug&function” installation capability. Analogous considerations apply, of course, to the already nearly fully integrated non-pumped storage collector systems of project goal (2).

Further cost reductions and performance improvements for solar-thermal systems on the component level may more directly arise from a material switch to polymers. For example, glazed flat plate collectors and vacuum tube collectors are currently manufactured in time-consuming and cost-intensive manufacturing processes requiring different material classes (metals for absorber, trough and frame; inorganic materials for selective absorber coatings, thermal insulation and glazing; and organic materials such as wood or plastics for the frame, the thermal insulation or the sealing). Metals, in particular copper used for absorbers and hydraulic piping, have been subject to significant price increases as a result of a shortage of capacities and resources. Polymeric collectors and polymer piping but also other system components such as storage tanks or heat exchangers based on polymeric materials, allow for significant cost reductions when taken together and integrated in a proper manner.

To a certain extent (also referring to work in *SolPol-1/2* by some of the consortium partners), polymeric materials are already in use for various solar-thermal components. The advantages related to the use of polymers include functional improvements, weight and cost reductions and - last but not least - more freedom in design to meet the aesthetic demands of architects and end-users. Moreover, as a result of their property profile, which may be tailored to specific requirements and applications, together with their low density (light weight), polymeric materials use “less to do more”, thus also contributing to resource preservation (Wallner and Lang, 2005).

Considering all of these aspects, it seemed imperative to further explore the potential of new materials to continue to develop the solar-thermal market by enhanced technical innovations. Thus, novel polymeric materials and their implementation in solar-thermal systems are increasingly recognized as key technology for the attainment of mid- and long-term development targets of the solar-thermal industry (Weiss and Biermayr, 2009; Fink et al., 2009; Fink and Preis, 2014). The crucial importance of novel material technologies is also recognized by the *European Technology Platform on Renewable Heating and Cooling* (Stryi-Hipp et al., 2012), and polymer technologies, in particular, are also defined as the key element of future innovations for low-cost solar-thermal systems in the US, as emphasized in a recent report by the National Renewable Energy Laboratory (Hudon et al., 2012).

Reflecting the above goals and the high potential of polymer driven technologies towards meeting these goals, the following **main deliverables** were defined for the project work.

- For low-cost pumped collector systems (DHW and SH applications):
  - Novel types of OHC collectors (max. stagnation temperature 95°C) with high polyolefin content in rigid and/or membrane design, optimized for plug&function capability to the remaining system
  - Novel types of collectors in engineering polymer and hybrid design (max. stagnation temperature 130°C) optimized for plug&function capability to the remaining system
  - Conception and definition of specific components that allow for a high integration into pre-fabricated.
- For high-quality non-pumped storage collector systems (DHW applications):
  - Improved and optimized single-loop integrated storage collector in rigid and flexible polymer-hybrid design
  - Novel double-loop systems with integrated heat storage in polymer and hybrid design
- Novel polymeric materials and semi-finished product types for solar-thermal systems:
  - High-performance polyolefins with improved high-temperature durability (95 °C)
  - Multi-functional master-batches for various solar-thermal systems components
  - Advanced multi-layer hybrid films (absorber membrane, flexible pipe, insulation and heat exchanger materials)
  - multi-functional or function-integrated material solutions for collector glazings or casings
- Advanced methods for durability testing of specimen and components under superimposed mechanical, thermal and environmental loading:
  - Test procedures and test catalogue

Research Program and Methodology

Reflecting the above goals, the research program of *SolPol-4/5* was designed to consist of the following 3 work packages (WP). Specific tasks have been allocated to each of these WPs which reflect the scientific approach, the topics of research along with the methodology applied, and the results to be obtained:

WP-01: Low-Cost Pumped Systems

Task 1.1: Systems definition and optimization

Task 1.2: Overheating controlled (OHC) collector with high polyolefin content in rigid and membrane design

Task 1.3: Drainback collector in rigid all-polymeric and hybrid design

Task 1.4: Conception of specific components, pre-fabricated/highly-integrated hydraulic stations and system integration

Task 1.5: Economic and ecological perspectives

<u>WP-02</u>: High-Quality Non-Pumped Systems

Task 2.1: Single-loop integrated storage collector systems

Task 2.2: Double-loop systems with integrated sensible heat storage

Task 2.3: Double-loop systems with integrated heat storage based on thermoformed components

Task 2.4: Economic and ecological perspectives

<u>WP-03</u>: Novel Materials and Test Methods

Task 3.1: High performance polyolefins for pressurized absorber applications meeting temperature, water/glycol and water/salt exposure requirements

Task 3.2: High performance polyolefins for liner applications meeting temperature and environmental exposure requirements (water, air, chlorinated water)

Task 3.3: Master-batch development for collector part applications and piping

Task 3.4: Advanced multi-layer hybrid films for collector system applications (membrane, flexible pipe, insulation and heat exchanger materials)

Task 3.5: Advanced methods for durability testing of specimen and components under superimposed mechanical, thermal and environmental loading

Reflecting the science-driven approach, in WP-01 and WP-02, theoretical (incl. modelling, simulation, polymer and solar physics) and advanced experimental work were combined

- to establish and describe the performance requirements for solar-thermal systems on various levels from the systems level to the component level to the material level,
- to optimize existing and to develop novel pumped and non-pumped polymer-based solar-thermal systems aiming at high degree of systems integration, installation simplification and thus cost reduction, and
- to deduce material performance requirements on an individual component level as a key pre-requisite to select and characterize proper commercial materials or to develop novel material grades where needed as part of WP-03 along with defining appropriate processing technologies.

In terms of material selection and testing, work on already existing commercial material candidates was directly included in the relevant Tasks of WP-01 and WP-02, whereas development of novel material compounds along with required screening tests was part of WP-03.

Literature:

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3 Results and Conclusions

The following results were achieved in the individual project phases (Year 1, Year 2, Year 3 and Year 4) of the SolPol-4/5 project within the overall project duration of 4.5 years (incl. a project extension of 6 months).

3.1 Year 1

3.1.1 Results and Conclusions

WP-01: Low-Cost Pumped Systems

Main results of WP-01 on system level are the elaboration of the "morphologic box" of different 17 system concepts with detailed characterization and evaluation as the basis for the development of forward-looking concepts for solar-thermal systems in the future. Further developed and extended calculation tools as supporting tools for detailed development of collectors with temperature limitation are now available or under final preparation. The first step of a fundamental study on solar-thermal system components and their functionalities has been elaborated as basis for the further development of significant improvement by increased pre-fabrication, creation of multi-functional units and using the advantages of polymer production techniques. Simulation studies showed that temperature limited polymer collectors (without stagnation periods due to steam) integrated in a system can equalize on system level disadvantages of a reduced nominal collector performance. Finally, first cost/ecology assessments comparing various heating systems for domestic hot water (DHW) and space heating (SH) for a range of different building standards using actual investment and energy costs and CO_2 emissions of the current energy mix in Austria reveal substantial benefits for polymer based solar-thermal systems, with combined PV/heat pump systems being the most competitive alternative.

WP-02: High-Quality Non-Pumped Systems

In Year 1 deficits regarding the single-loop integrated storage collector systems were analyzed on an existing system using practical and theoretic research. Solutions for critical components were worked out and elaborated. Furthermore, it was possible to determine material-specific requirements necessary for further research. For double-loop systems with integrated sensible and latent heat storages not only concepts were determined and evaluated but also preliminary theoretic models for the representation of specific system components were elaborated and validated. In terms of worldwide economic perspectives, at the end of 2012, about 75% of the glazed solar-thermal systems installed were non-pumped thermosiphon systems and 25% were pumped systems. With more than 50%, they also dominate current markets (new installed systems in 2013) in Sub-Sahara Africa (97%), China (95%), Latin America (85%) and Asia excl. China (80%).

WP-03: Novel Materials and Test Methods

The research work in the Tasks of WP-03 was highly science-driven with a strong and dominating involvement of the scientific partners. In the Tasks 3.2 and 3.5 advanced equipment for durability testing on specimen level was developed and implemented (Task 3.2: facility for simultaneous exposure of liners' surfaces in air and (chlorinated) water at constant oxygen pressure; Task 3.5: test setup for creep, stress relaxation and fracture mechanics testing of polymeric materials under superimposed thermal, mechanical and environmental loading). Research work in the Tasks 3.1, 3.3 and 3.4 was dealing with the development of novel immobilized stabilizers, high performance polyolefins for pressurized absorber applications, master-batch and material formulations for grey-colored pipings and fittings and high temperature resistant liners for seasonal hot water storages as well as polar ethylene-copolymer/polyamide materials and spectrally selective galvanic coatings for hybrid membranes and film laminates for thermal insulation structures. The TRL3-evaluation of materials for hybrid membranes and flexible pipe structures in Task 3.4 was performed and an ethylene-copolymer/polyamide-blend was selected for aging investigations.

3.1.2 Highlights

WP-01: Low-Cost Pumped Systems

A major highlight of WP-01 was within Task 1.1 the definition and elaboration of potential system concepts for pumped solar-thermal systems within actual and new boundary conditions making use of novel components in partial polymer or hybrid design. The work was based on an extra developed tool in order to build up a systematic structure of system concepts resulting in a so-called "morphologic box", which also can be used to further assess the concepts based on weighted ratings for several categories (see Fig. 3.1). After numerous discussion and brainstorming sessions and subsequent more detailed analysis and evaluation, 17 different system concepts were defined, described and characterized in detail and rated (SWOT analysis). This provides an excellent foundation for the next step of further detailing these concepts with regard to specific boundary conditions (local/regional climate, market aspects, service requirements, etc.). As a further highlight, the adaptation and improvement of existing simulation tools for solar-thermal systems may be mentioned, as they will allow guiding future work in terms of specific systems optimizations.

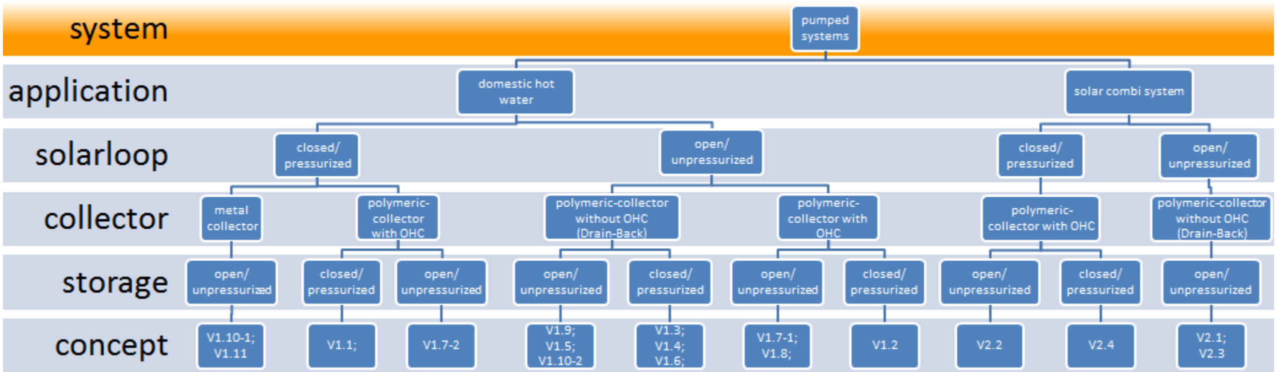


Fig. 3.1: Categorization of pumped solar-thermal systems for a systematic SWOT analysis.

WP-02: High-Quality Non-Pumped Systems

An essential element in developing the internal coating for the metal pipes of the single-loop collector storage as well as the polymer pipes is to know the thermal stress. Not only the maximum thermal stress but also the frequency of these stresses play an important role. Based on the preliminary results of the

EU-funded project SCOOP, the theoretic storage collector model was matched with the simulation program (Polysun 6.2). Annual simulations for the worst-case scenario (no domestic hot water demand) were calculated and expanded with the expected surface temperatures. For this purpose the relation between the temperature gradient between the medium and the surface of the side of the metal pipe facing the sun and the irradiation was calculated and validated using measured data. Using the hourly data of the medium temperatures (from Polysun 6.2) for the storage collector as a basis, this was expanded with the temperature gradient according to the climate conditions (irradiation on the inclined collector area). In the next step, the occurring temperatures were analyzed and the frequencies for one simulation year were calculated for five reference locations (see Fig. 3.2).

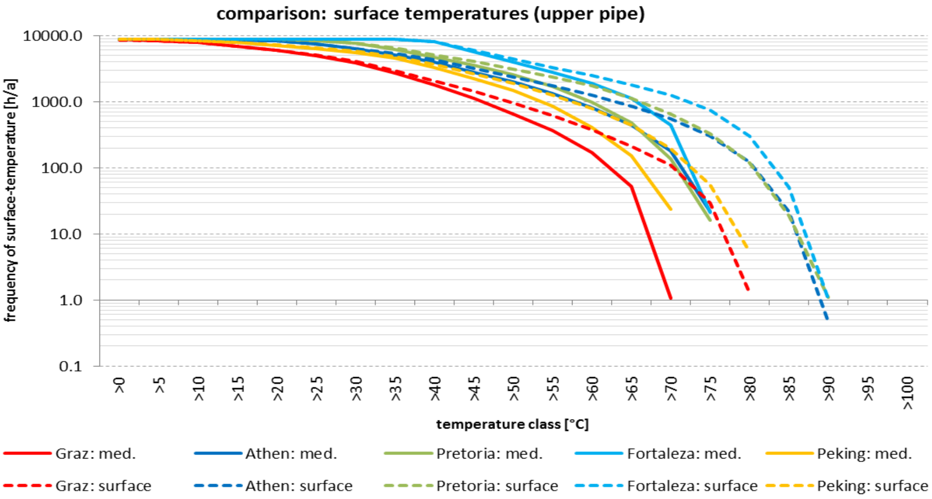


Fig. 3.2: Cumulative frequency of the medium and surface temperature of the storage collector without domestic hot water demand (worst-case scenario) for five different locations.

WP-03: Novel Materials and Test Methods

The consideration of service-relevant loading conditions and failure mechanisms is of high relevance for reliable durability testing and lifetime assessment of materials for demanding applications. In WP-03, two different durability test facilities were developed and implemented for the comprehensive characterization of the long-term behavior of polymeric materials for pressurized absorber and heat storage applications, which may be considered unique worldwide. To assess the time dependent mechanical behavior and the fracture behavior under combined mechanical, thermal and environmental loads, media containments for monotonic and cyclic electro-mechanical material test systems were implemented and are already used for black-pigmented polyolefin and polyamide based solar absorber materials. Furthermore, a durability and lifetime test facility for high temperature resistant geomembranes (liners) for (seasonal) hot water storages was conceived, evaluated and implemented. The liner testing system allows for simultaneous exposure of membranes with thickness in the mm-range to hydrostatic pressure, air on the outside and (chlorinated) water with a defined oxygen content onto the inner liner surface. In Fig. 3.3, the CAD construction of the liner test facility and the sample holder is depicted. To allow for outside hot air contact and negligible topographical changes a metal fabric was inserted into the pressure resistant sample holder plate. Both test facilities have been implemented and are already used for accelerated durability characterization and lifetime assessment of novel material grades in a lab environment.

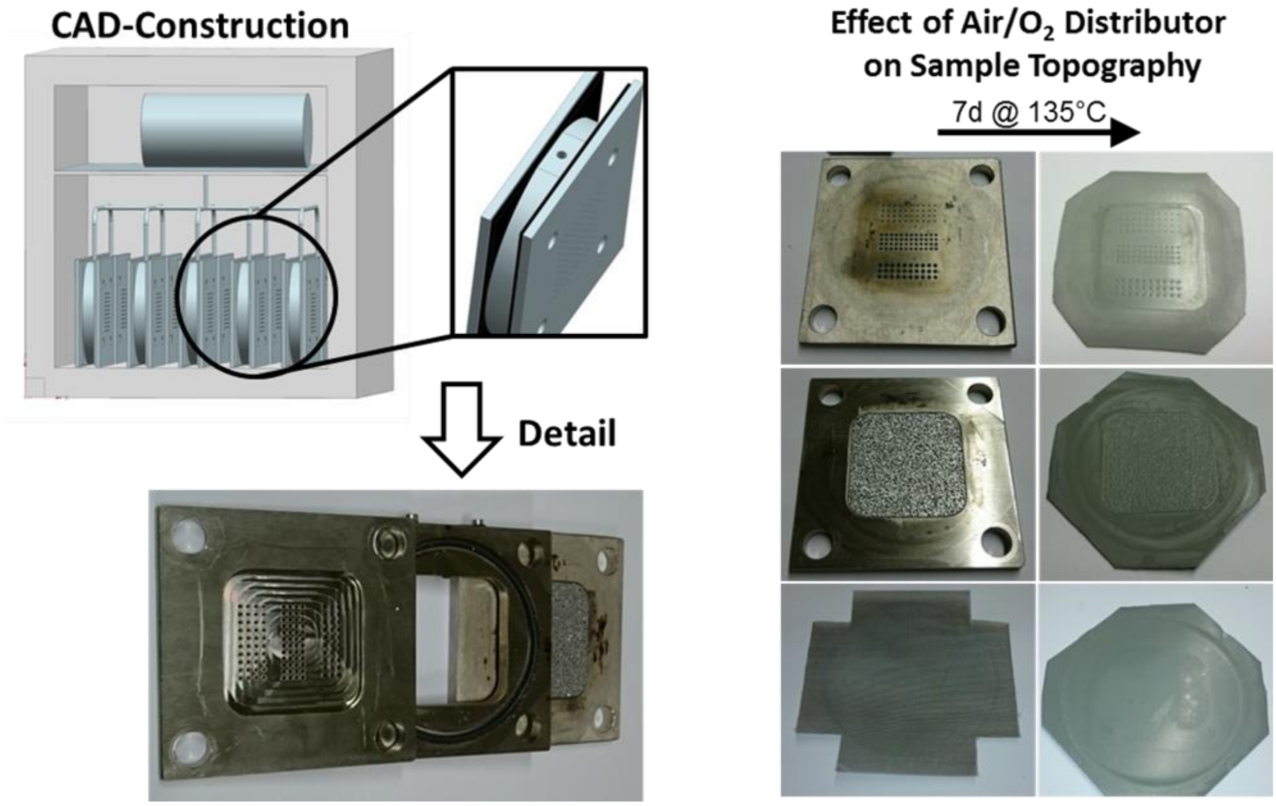


Fig. 3.3: Facility, sample holder and air distribution inserts for accelerated and simultaneous aging of liners of heat storages in air and (chlorinated) water at constant oxygen pressure.

3.2 Year 2

3.2.1 Results and Conclusions

WP-01: Low-Cost Pumped Systems

Main results of WP-01 in Year 2 are the detailed loading conditions (temperature and pressure distributions) for the selected pumped systems with polymer-based collectors and the deduced cost reductions potentials, which are potentially even slightly higher than 50 %. Furthermore, levelized costs of solar heat (LCOH) in the range from 3 to 6 c€/kWhth were established for the novel systems and compared to reference systems for different climate zones and applications (domestic hot water and combi systems).

For the fully overheating controlled collector (T_{max}: 95 °C) with high polyolefin content it was shown that the system performance can be significantly increased by avoiding stagnation. For this collector type, functional models of ball and piston valves were designed and prepared by rapid prototyping. As to the collector in engineering polymer and hybrid design (T_{max}: 135 °C), back ventilation was classified as the most promising and technically feasible configuration. For both collector types, membrane absorber designs (geometry and cutlines) were implemented and validated. Furthermore, polyamide based glass-fiber reinforced materials for the mounting structures were compounded, characterized and selected.

Regarding specific system components, significant advances were achieved for heat exchangers (hollow fiber heat exchangers based on polypropylene). Finally, facilities for lab-scale testing of heat exchangers and storage tanks were implemented.

WP-02: High-Quality Non-Pumped Systems

In Year 2, the work has been continued to remove the existing deficits in the design of single-loop integrated storage collectors (Solcrafte® of GREENoneTEC) in rigid hybrid design. Cost efficient solutions for specific components were analyzed, and new processing routes for materials for specific components have been (and are being) developed: end caps (electron-beam cross-linking), venting valves, storage pipes and coating (liner), glazing and insulation. The results show a cost reduction potential for the cover and the transparent thermal insulation in the range from 20 to 80 % compared to the reference system (Solcrafte). For the back-insulation, a cost reduction of 7 to 20 % seems feasible. For the all-plastic storage collector system (based on cushion pad), thermal welding tests and computer-aided designs were performed.

Concerning the double-loop systems, various designs were assessed with functional models and numerical simulations: the selected configuration is a direct hot water draw-off from storage (no hot water heat exchanger) and includes harp design for storage pipes connection.

Overheating control (via a back cooler) was shown to offer a great potential to use low-cost polymeric materials in thermosiphon systems. A design has been carried out, achieving a thermosiphon system with high-share polymer content. Its lightweight and potential low cost are attractive. Nevertheless, the manufacturing processes are not yet clear and may need further assessment and optimization.

WP-03: Novel Materials and Test Methods

As in Year 1, the research work of WP-03 in Year 2 was highly science-driven with strong and dominating involvement of the scientific partners. In Task 3.1 a novel antioxidant with a melamine center and aliphatic linkages to the phenolic functional groups was synthesized, up-scaled in the gram range and used for polypropylene based absorber compounds. Due to the unique chemical structure, a significantly improved stability in humid environments is expected. Furthermore, it was shown in Task 3.1 that carbon nanotubes as “black pigments” do not outperform conventional carbon black as “black pigments” for polypropylene absorbers (in fact, the latter even turn out to be superior, probably also due to dispersion problems with carbon nanotubes).

Regarding the performance of the novel absorber materials, in a first series of experiments, the same ranking of the grades was obtained from global aging experiments (without superimposed mechanical loads) and local aging experiments (with superimposed mechanical loads). It is unclear however, whether this result can be generalized or whether conditions may exist, where differences arise.

To describe the endurance times of polyolefin-based, heat storage liner materials at service temperatures of 60 to 90 °C (Task 3.2), non-linear fit models accounting for temperature dependent aging mechanisms were implemented and validated. For polyolefin based liner, collector casing and piping materials as well as polyamide grades for injection molded system components (e.g., pumps, valves) optimized master-batches were formulated, converted to compounds and characterized as to their long-term behavior under service relevant conditions (Task 3.3). For the first time, synergistic/antagonistic effects between a variety of hindered amine light stabilizers and phenolic antioxidants in polypropylene grades were established and elucidated.

As to the investigated multi-layer hybrid laminates (Task 3.4), significant advances were achieved for selectively coated solar absorber membranes, corrosion inhibiting functional layers and polyester/aluminum laminates for thermal insulation structures.

Finally, in Task 3.5 the unique facilities for testing of materials under superimposed mechanical, thermal and environmental loading conditions were further devised and extended for cracked round bar specimens and ionized/chlorinated hot water environments.

3.2.2 Highlights

WP-01: Low-Cost Pumped Systems

A highlight of WP-01 was the conception and design of overheating control valves needed for fully overheating protected collectors with high polyolefin content (Task 1.2). The novel valves use pressure differences to switch between the on (back cooler mode) or off (system mode) state. A ball valve was designed which closes the back cooler when the pump is on. Furthermore, a piston valve with spring was designed which connects the absorber to the back cooler when the pump is off (see Fig. 3.4). Due to this advancement, work step 1.2.4 was started ahead of schedule with rapid prototyping of two selected valve constructions. Furthermore, a facility for lab-scale testing of such valves was implemented.

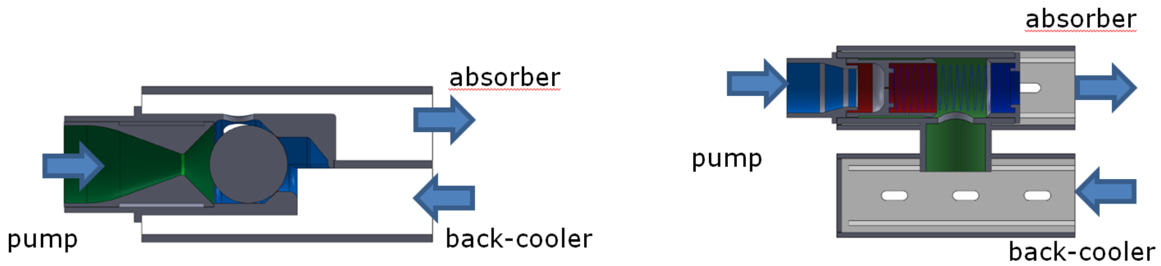


Fig. 3.4: Designs for ball (left) or piston with spring (right) valves needed for fully overheating controlled collectors with high polyolefin content.

Further highlights of WP-01 are the welded membrane absorber mock-ups with optimized geometrical and cutline designs, the establishment of an international collaboration on hollow-fiber heat exchangers made from polypropylene and the concepts for small hot water storage tanks and large polymer-based tanks for combi systems.

WP-02: High-Quality Non-Pumped Systems

Substituting the metal components with polymer components opens up a great potential for cost reductions with simultaneous performance improvements. In work step, 2.3.2 a thermosiphon system with a high proportion of polymeric components has been designed (see Fig. 3.5). All components are designed in such a way that they can be produced in different plastics processing technologies. In the first development step, the system consists of a polymeric body and matching cover, a polymer based unpressurized storage, a solar glass with metallic absorber located behind and a corrugated tube heat exchanger for hot water preparation. One of the biggest advantages of the polymer system is the lower weight. The entire system, collector and storage, can be pre-assembled and handled as one single piece. This allows a faster installation in comparison to a metallic reference system. The system design is also suitable for both, parallel-to-roof mounting and flat roof installation.

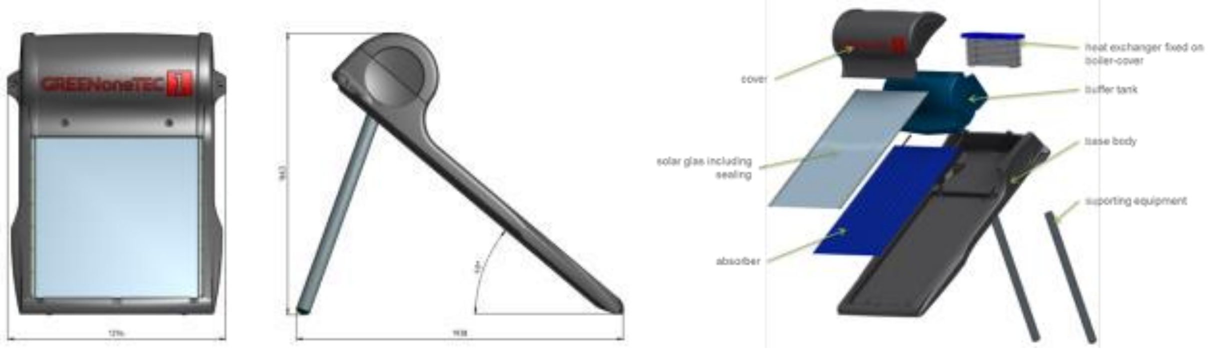


Fig. 3.5: Design study of a polymer thermosiphon systems (source GREENoneTEC).

Furthermore, manufacturing costs for individual components (base body, cover, buffer tank) and investment costs for the tools required were estimated for rotation-molding (see Fig. 3.6). There is further cost reduction potential to be tapped: the manufacturing process currently considered due to small manufacturing quantities, i.e. rotation molding, is not the most cost-effective process.

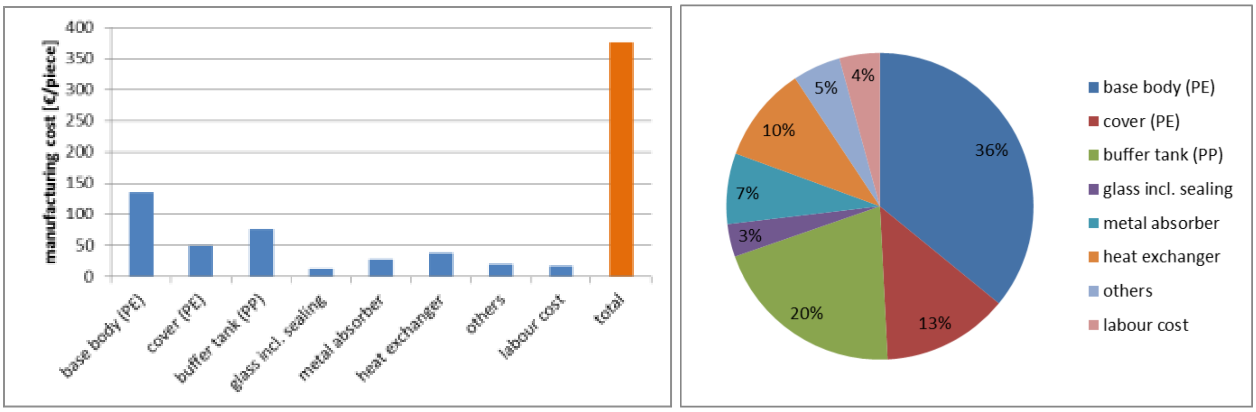


Fig. 3.6: Polymer thermosiphon system: cost estimation (left) and share of costs (right). (source GREENoneTEC).

WP-03: Novel Materials and Test Methods

The consideration of service-relevant loading conditions and failure mechanisms is of high relevance for reliable durability testing and lifetime assessment of materials for demanding applications. In WP-03, the existing equipment for testing of specimen under superimposed mechanical, thermal and environmental loading conditions was significantly developed further. Major steps included the design, simulation, manufacturing and implementation of novel components, and the system is now nearly fully operational. It was conceived to allow for continuous flow and exchange of the medium, which is of utmost importance especially for chlorinated drinking water, and the system is now being tested. In Fig. 3.7 (left), the unique setup for cyclic fracture mechanics tests in temperature chambers (top) or containments with continuous flow of media (bottom) is depicted schematically. The setup is now extensively being tested, and it was already used to generate first results. For example, the crack growth behavior of the polypropylene based absorber material developed in SolPol-2 in different environments is also shown in Fig. 3.7 (right). At the temperature of 95°C, the fatigue crack growth rates were enhanced in air compared to the various water media. The result, with air as the more critical environment compared to deionized water at least at 95°C, is in good agreement with conventional aging data obtained by investigations of micro-sized specimen without superimposed mechanical loads. Main advantages of this novel approach are the significantly shorter testing times (factor of more than 20) and the superposition of loads, which is of relevance for components in pressurized systems.

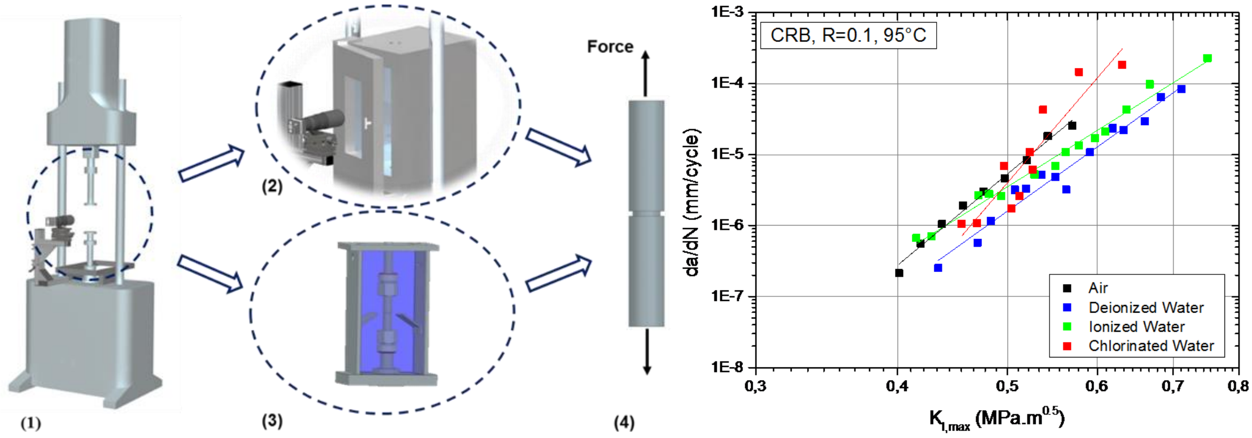


Fig. 3.7: Setup for cyclic fracture mechanics test in temperature chambers (top) or containments with continuous flow of media (bottom) using cracked round bar specimen (CRB) (left) and crack growth behavior of the polypropylene based absorber material developed in SolPol-2 in different environments (air; deionized, ionized and chlorinated water) at 95°C.

3.3 Year 3

3.3.1 Results and Conclusions

WP-01: Low-Cost Pumped Systems

Main results of WP-01 in Year 3 are the full conception and definition of the pumped domestic hot water system with non-pressurized loop based on a polymer collector with back cooler. For the essential components needed for this system, loading conditions and property requirements were deduced and used to select specific polymer grades. Furthermore, the most important processing steps including extrusion, injection molding and welding were established. Compared to reference systems for different climate zones and applications (domestic hot water and combi systems), a high potential was deduced for overheating controlled collectors with black absorber and back cooler.

For the fully overheating controlled collector (T_{max}: 95 °C) with back cooler functional model collectors with ball and piston valves were designed, prepared and tested. A significantly better and more reliable switching performance was obtained for the ball valve. As to the collector in engineering polymer and hybrid design with back ventilation it was shown, that this measure allows for limitation of the stagnation temperature to about 105°C. However, for extruded PP based absorber sheets this temperature level is already close to the heat deflection temperature limit resulting in significant sagging of the ventilation gap. Hence, it was decided to use the fully overheating controlled collector with back cooler for the pumped collector system. Lab-experiments for upscaling of membrane absorbers to about 1 m^2 revealed significant problems of this absorber type associated with wrinkles, warpage or load-limiting welding defects. Collectors with membrane absorber designs will not be used for the model system in Task 1.4.

Regarding the eco-balance of the investigated pumped system in a service-specific manner, values for the energy payback time (EPBT) were found to amount to less than 2 years for all six world regions investigated, in some regions EPBT values even less than one year were found. Compared to a collector service life of 20 years, this leads to energy amortization factors of more than 10 (!) for all world regions.

WP-02: High-Quality Non-Pumped Systems

In Year 3, the work has been continued in the evaluation of the design and construction of specific system components considering appropriate processing methods and cost-efficient materials, which meet the requirements. Cost efficient components (cover, insulation) have been analyzed in full-scale models. The design of the pressurized storage has been optimized (vertical harp design) based on the results of Task 2.2. Concerning the use of long fiber reinforced thermoplastics (LFRT) the design will be evaluated in terms of manufacturability of the two half shells and the joining geometry for gluing will be specified in close cooperation with an adhesive specialist to introduce primarily shear and reduced tensile loads. In the next reporting period, the joining technique will be characterized on specimen level and optimized if necessary. Functional models will be manufactured and analyzed.

Concerning the double-loop systems, two series of functional models have been tested in real environment according to the norm ISO 9459-2 1995 and analyzed in detail. The experiments enabled a characterization of the collector concepts: (i) energy yields under different daily solar irradiations and different ambient temperatures; (ii) draw-off profiles horizontal and vertical harp; (iii) stratification behaviors, charging and discharging; (iv) heat losses; (v) PV-pump operation. A proof of concept has been performed of both configurations (indirect and direct double loop systems). Regarding the TRL-5 evaluation, the system configuration with vertical harp and direct integrated solar loop showed very good performance. Additionally optimization potentials have been detected and recommendations for the further technology development have been derived.

The design of the thermosiphon system with high-share polymer content has been elaborated in detail. The assessment of the overheating control mechanism via ventilation (Task 1.3), which shall be integrated in the TSS, showed that the evaluated valve begins to open at a temperature of 90°C and is fully open at 105°C. This temperature range is ideal to reach high performances during operation, but it is very close to the evaporating temperature of the fluid in the unpressurized storage tank. It seems that the opening temperature for the overheating control should be lower. Therefore, an alternative shape memory alloy (SMA) spring and/or other mechanisms have to be selected with lower activation temperatures.

Regarding the eco-balance of the investigated integrated storage collector system in a service-specific manner, values for the energy payback time (EPBT) were found to amount to about 1 year. Compared to a collector service life of 10 years, this leads to energy amortization factors of more about 10 (!) for all world regions. Similar values are obtained for existing commercial systems. The rather high energy amortization factors along even outweigh any potential effects of recycling, as for all cases the energy savings in terms of recycling rather than using virgin material amounts to just a minor portion of the total service life energy yield.

WP-03: Novel Materials and Test Methods

For the novel, black pigmented *SolPol*-PP block copolymer with ß-nucleation, 50% higher lifetime values for extruded absorbers in pumped collector systems compared to a state of the art PP material in α-crystal form were deduced. The values varied between 20 and 47 years depending on the material and the installation site. Furthermore, an even better hot air aging behavior was obtained for a PP grade with the novel *SolPol*-stabilizer with melamine center and aliphatic linkages to the phenolic functional groups. Due to the fact that so far only failure times at 135°C are available, no lifetime estimation was possible for this unique material. In addition, the novel *SolPol*-liner materials for hot water storages based on PP blends exhibited a superior lifetime performance (factor of about 5 higher) compared to commercial PE grades. For the polyolefin-based collector casing materials the antagonistic weathering effects between a variety of hindered amine light stabilizers and the hydrolysis resistant antioxidants IX1330 was elucidated. Of high relevance for non-pumped integrated storage collectors are the established relationships between the primary structure of polyamides, the stabilizer package and the glass fiber content on the crack-growth behavior under superimposed thermal, environmental and mechanical loads. Therefore, the unique facilities available for superimposed environmental fatigue testing at JKU-IPMT were used. The existing test setup was extended with a continuous flow chamber for chlorinated hot water with adjustable chlorine content up to 10 ppm, which itself is a world novelty.

3.3.2 Highlights

WP-01: Low-Cost Pumped Systems

A highlight of WP-01 in the reporting period was the conception and design of the pumped domestic hot-water system with a non-pressurized loop based on a polymer collector with back cooler (see Fig. 3.8). For this novel system model, collectors with extruded PP absorber and back cooler were implemented and evaluated. Furthermore, a functional model of a ball overheating control valve was manufactured and tested in a lab environment. Finally, a compact storage unit with coiled heat exchanger was conceived and partly built using semi-flexible piping and push-fit-connectors. For the heat storage tank a multi-purpose injection-molded, top and bottom cover was designed. Property requirement profiles for materials were defined and used to select a specific PP grade with extrusion, injection molding and welding capability.

Fig. 3.8: Pumped domestic hot water systems with non-pressurized loop based on a polymer collector with back cooler.

WP-02: High-Quality Non-Pumped Systems

An essential step forward in developing of the integrated storage collectors has been achieved in this reporting period especially in the design of the polymer-based pressurized storages. Based on a theoretical analysis and on outdoor performance tests, an optimized storage design for the use in the single-loop as well as in the double-loop systems has been identified (see Fig. 3.9). The elaborated design combines the attributes of improved draw-off profiles for the single- and double-loop systems and an efficient and effective stratification during storage charging via a PV pump. The multifunctional design leads to a multiple benefit for the project partner GREENoneTEC and thereby to a cost-optimized component, based on the LFT manufacturing process, which can fulfil highest system efficiency and comfort requirements in different climate zones. Furthermore, based on results of the previous studies, auxiliary collector components and materials have been selected involving the entire consortia value chain.

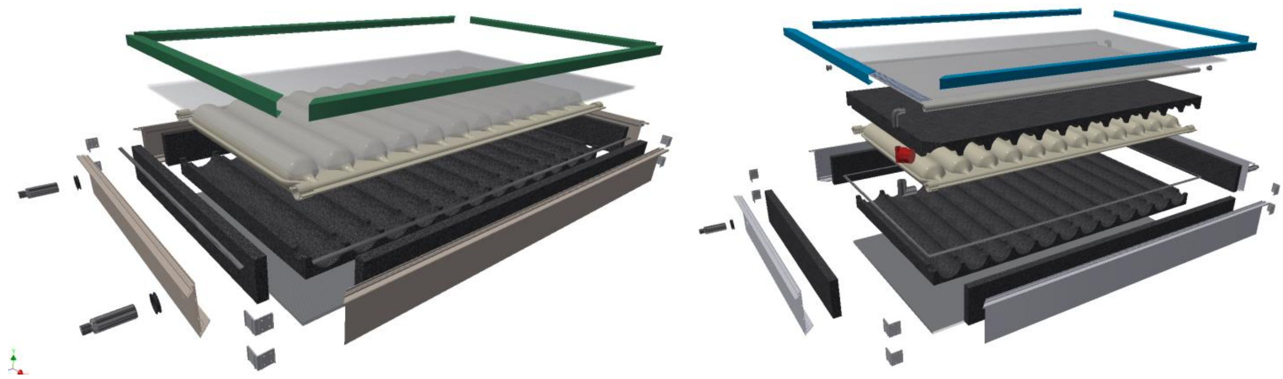
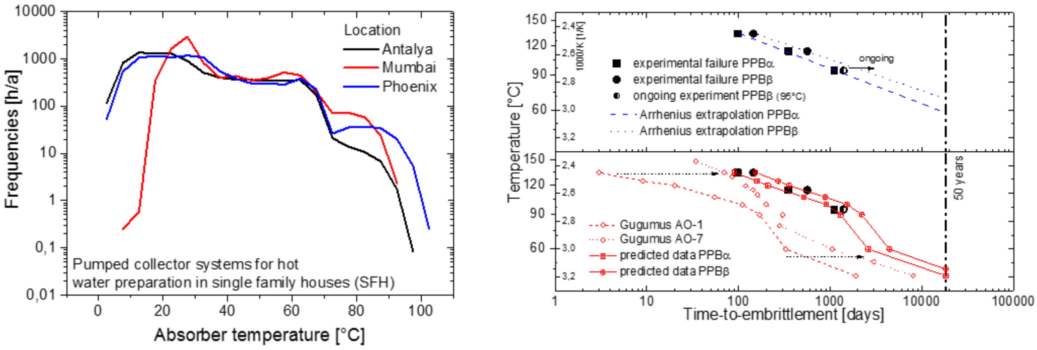


Fig. 3.9: 3D model of the single-loop (left) and double-loop (right) integrated storage collector, with the multifunctional pressurized storage.

WP-03: Novel Materials and Test Methods

Novel and innovative materials with improved performance, especially in the category of polyolefins, are of utmost importance for cost-efficient solar-thermal systems for hot-water preparation. In WP-03, various polyolefin grades with differing primary structure, pigmentation or stabilizer packages are developed and characterized as to the aging behavior under service-relevant conditions. In Fig. 3.10, the scientific approach for lifetime assessment of solar absorber materials based on site and system specific temperature load profiles, extrapolated endurance times and accumulation of damages is depicted. The foundation on which the lifetime assessment methodology is based on is of advanced and outstanding scientific nature, providing for a series of peer-reviewed publications in highly recognized solar and polymer science journals. This approach was also used to assess the lifetime of the best-performing, novel *SolPol* polypropylene grade with ß-crystalline structure (PPBß) and a state of the art, black PP material for swimming pool collectors. For the novel *SolPol,* absorber material an improvement in lifetime by 50% was achieved.



Lifetime modelling:

- *Extrapolation by Arrhenius and Gugumus approach*
- *Cumulative damage model (Miner's rule)*
  → *lifetime* (t_f)

$$^1/_{t_f} = \sum_{i=1}^{i=n} \left[\left({}^{t_i}/_{t_{tot}} \right) / t_{fi}(T_i, \sigma_i) \right]$$

	Lifetime, years	Antalya, TR	Mumbai, IN	Phoenix, US
Arrhenius	PPBα (state of art)	45	41	41
	PPBβ (*SolPol* grade)	47	43	43
Gugumus	PPBα (state of art)	24	20	23
	PPBβ (*SolPol* grade)	34	29	32

~ 50% improved performance!

Fig. 3.10: Approach for lifetime assessment of black-pigmented solar absorber materials and lifetime values obtained for a state-of-the-art material (PPBα) and the novel *SolPol* grade (PPBß).

3.4 Year 4

3.4.1 Results and Conclusions

<u>WP-01</u>: Low-Cost Pumped Systems

Main results of WP-01 in Year 4 include the detailed development and testing of high performing polymer collectors with full overheating control (by back-cooling and venting), the conception and evaluation of different polymer-based hot water storages, the lab-scale testing of pumped polyolefin-based collector systems for warm climate zones (current mass market) and the deduction of levelized costs of heat for such systems. Using the back-cooling principle and an optimized ball valve, it is possible to limit the maximum absorber temperature to 95°C and to achieve adequate efficiency values $\eta_{0,05}$ of 0.3. Furthermore, a fail-save switching behavior of the novel overheat control valve (OHC) was proven by on-off cycling tests and long period tests for more than one year. Similar efficiency values but slightly higher stagnation temperature around 105°C were obtained for a back-vented polyolefin collector. Also for this collector type a novel temperature controlled valve was successfully developed. For the pumped collector systems, various polymer-based solar heat storages including integrated hydraulic units and heat exchangers were designed and evaluated under lab conditions. For the best storage with corrugated, coiled heat exchanger pipe, a tapping efficiency of 59% was achieved. By system simulations for a solar domestic hot water, system it was shown that it is possible to reduce the solar heat storage volume from 300 to 100 liters allowing for the same solar fraction. This reduction in heat storage is related to the consequent avoidance of stagnation periods by full overheat protection. For the investigated solar-thermal domestic hot water systems, a solar fraction of around 25% was achieved for low energy single family houses using also the heat storage effects of floor heating building mass activation. This value is similar to state-of-the art solar combi system with standard flat plate collectors using only the water tank as solar heat storage. The levelized costs of heat of the investigated pumped all-polyolefinic collector system is ranging from 1 to 3 €ct/kWh depending on the installation site. These values are a factor of 3 to 5 lower compared to levelized costs of solar-thermal heat for conventional small pumped systems in Central Europe (-60 to 80% cost reduction). However, compared to LCOH data of thermosiphon systems mainly used in warm climate zones, the levelized costs of solar-thermal heat are in the same range. And yet, the main advantage of the pumped polyolefinic system is the high design flexibility (e.g., positioning of the storage tank). In absolute values, an ultra-low-cost pumped DHW system made from polyolefins at a purchase price of $180 was realized in *SolPol-4/5*. A main problem regarding full commercialization of the findings are relatively high annual production and sales volumes of about 100.000 systems/year which are needed to exploit the full cost advantages.

WP-02: High-Quality Non-Pumped Systems

In Year 4, the single loop integrated storage collector (ISC) system has been brought to a full-scale functional model. The geometry for a permanent connection of two half shells has been specified and optimised in details via FEM simulations based on the mechanical characteristics of the treated material specified in WP-03. Gluing as joining technique has been characterized at specimen level with different glues and the best performing glue has been selected for the functional model. Functional modules of the pressurized storage, consisting of two vertical pipes, have been manufactured with the long fiber thermoplastic (LFT) molding manufacturing process, and burst pressure tests in a variety of different conditions (cold water (24 °C; 5.4 bar); hot water (79.3 °C; 4.2 bar)) were carried out. Finally, a full-scale single-loop ISC based on functional modules connected in parallel has then been assembled and tested at the outdoor test rig of AEE INTEC. The performance is promising and this collector is especially suitable for regions with corrosive water.

The thermosiphon system, manufactured with high share of polymer materials, has been tested in outdoor conditions. The heat exchanger immerged in the pressure-less storage is satisfying, limiting the temperature hub from storage to hot water to 10 K. The need of over-heating control in case of stagnation has been observed, as the pressure-less storage should not reach 100 °C to avoid evaporation. Subsequently, a temperature-controlled back-ventilation, based on work from Task 1.3, has been implemented and tested. Further improvements of the functional model have been proposed for satisfactory cooling effect.

Compared to thermosiphon systems with vacuum tubes the costs of the developed polymeric ISC systems are still somewhat higher, hence further concepts were conceived and assessed as to their potential for further cost reductions (polymeric ISC with expanded PP (foam) frame; 100 $ system for extremely low income regions. The latter work was performed to replace the originally envisaged work on the market potential and economic effects of polymeric collector systems.

WP-03: Novel Materials and Test Methods

For the novel, black pigmented SolPol-PP block copolymer with ß-nucleation, 50% higher lifetime values for extruded absorbers in pumped collector systems compared to a state-of-the-art PP material in α-crystal form were deduced. The values varied between 20 and 50 years depending on the material and the installation site. An even 20% better hot air aging behavior was obtained for a PP grade with the novel SolPol-stabilizer with melamine center and aliphatic linkages to the phenolic functional groups. For the novel SolPol-liner materials for hot water storages based on PP blends, a comprehensive endurance time model including material thickness and temperature effects was established. The specialized PP grades with unique stabilizer package exhibited a superior lifetime performance compared to commercial PE grades (factor >3 better). For medium (50 to 85°C) and high (60 to 95°C) temperature storages, lifetime values of more than 50 and 30 years, respectively, were deduced for the best-performing PP grade. For non-pumped integrated storage collectors, novel polyamide grades with glass fiber reinforcement and hydrolysis stabilizer package were developed. Interestingly, the ranking of the materials was similar regarding their global aging behavior (without superimposed mechanical loads) and their local aging behavior or crack-growth behavior under superimposed thermal, environmental and mechanical loads. For this purpose, worldwide unique test facilities were implemented at JKU-IPMT for superimposed environmental fatigue testing that allow for accelerated and efficient screening of novel materials for solar-thermal applications.

3.4.2 Highlights

WP-01: Low-Cost Pumped Systems

A highlight of WP-01 in Year 4 was the full implementation and prove of concept for polyolefin-based pumped collector systems with levelized costs of heat reductions by -60 to -80% compared to reference domestic hot water systems in Central Europe. Hence, the overall goal of *SolPol-4/5* regarding performance-based cost-reductions for all-polymeric pumped collector systems was even excelled. For the current mass market in warm climate zones, dominated by thermosiphon systems, the novel pumped systems are in a similar costs range. However, the pumped polyolefinic system allows for high design flexibility, especially regarding the positioning of the storage tank (see Fig. 3.11). Moreover, the main advantage of the pumped polyolefinic system is the high design flexibility (e.g., positioning of storage tank). For an ultra-low-cost pumped DHW system made from polyolefins (~2 m² collector area, 100 l storage tank), a purchase price of $180 was deduced. For such systems various types of compact storage units with coiled heat exchanger were implemented, tested and optimized. For the best storage model, a tapping efficiency of 59% was achieved.

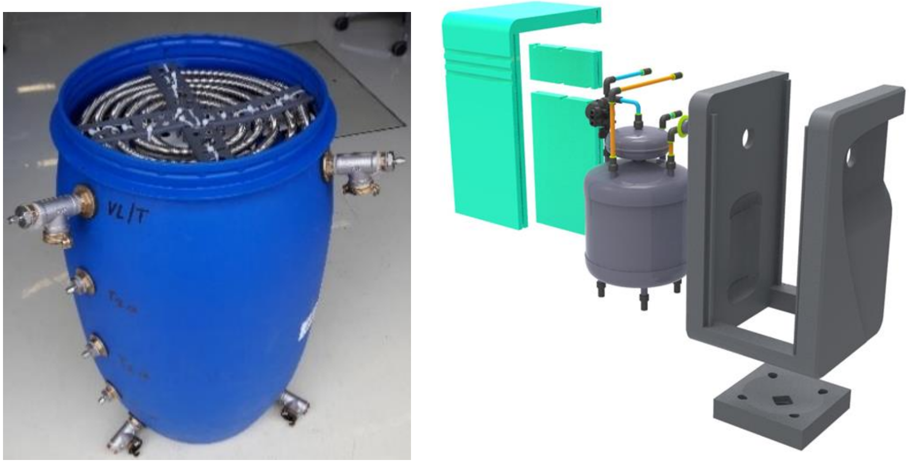


Fig. 3.11: Functional model of the heat store and concept for an all-polymeric heat store with integrated hydraulic unit and piping.

<u>WP-02</u>: High-Quality Non-Pumped Systems

Based on all previous developments in WP-02, a full-scale functional model of single loop Integrated Storage Collector (ISC) system has been manufactured (see Fig. 3.12). It is composed of two glued polymer half-shells shaping 12 pipes connected vertically in parallel. The 12 vertical absorber-storage pipes are obtained from assembling 6 molded elements made of 2 pipes each. The pipes are made of two molded half-shells glued together. The half shells are obtained through long-fibre reinforced thermoplastics (LFT) manufacturing process. In the functional model, all storage pipes are connected with a copper pipe screwed on the inlet connection at the bottom and on the outlet connection at the top. The storage pipes are insulated at the back and covered with a twin-wall polycarbonate sheet on the front side. This full-scale functional model has been successfully tested in outdoor conditions. The results of this polymer-based ISC system indicate similar cool-down at night, a slightly lower efficiency than the metal-based Solcrafte®, but similar efficiency to common thermosiphon systems. Most of all, the polymer based collector resists much better to corrosion which makes it very suitable for regions with high chloride concentration in water and in the atmosphere (esp. in coastal areas).

Fig. 3.12: Left: detailed construction of the single loop system. Right: Full-scale functional model out of plastic absorber-storage pipes.

WP-03: Novel Materials and Test Methods

Novel and innovative materials with improved performance, especially in the category of polyolefins, are of utmost importance for cost-efficient solar-thermal systems for hot-water preparation. In WP-03, various polyolefin grades with differing primary structure, pigmentation or stabilizer packages were developed and characterized as to the aging behavior under service-relevant conditions. Exemplarily, in Fig. 3.13 the dependency of the endurance times of established polyethylene and novel polypropylene materials on (specimen) thickness and temperature is depicted. Based on comprehensive aging data for micro- and macro-sized specimens, a unique model has been established and validated, which allows for reliable lifetime assessment. In a series of peer-reviewed publications in scientifically highly recognized journals, the results of this research on the systematic assessment of PE and novel PP grades as to their long-term performance have been published. The best-performing, novel SolPol polypropylene random copolymer grades with special crystalline structure and unique additive packages comprising different stabilizer types outperform state-of-the-art PE-grades for hot water applications by a factor of more than 3 in lifetime.

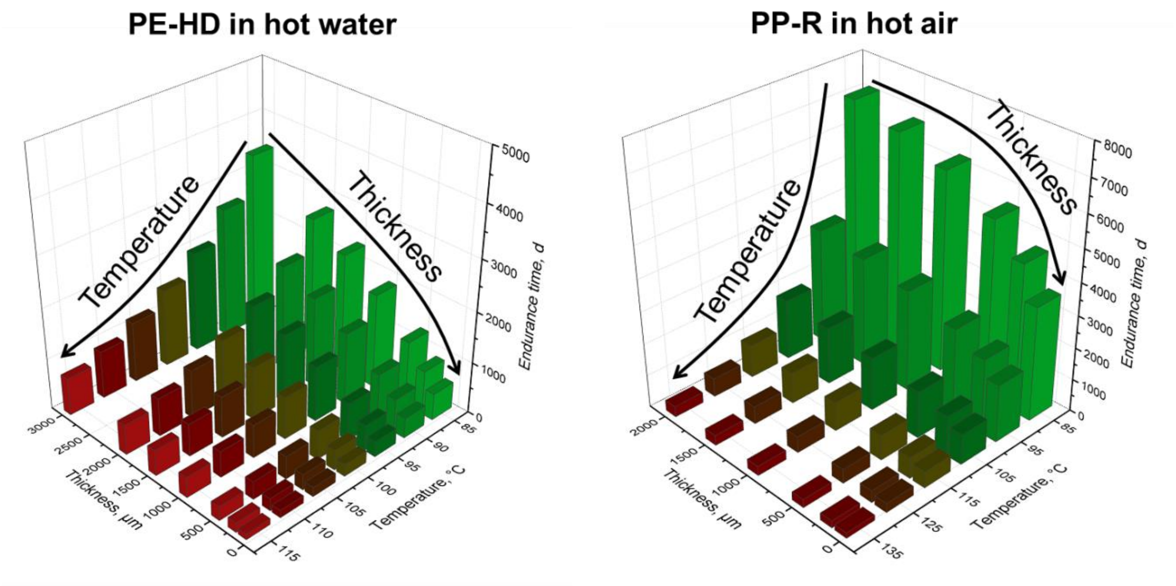


Fig. 3.13: Effect of temperature and thickness on the endurance times (d…day) of the best performing PE liner in hot water (left) and a novel PP liner in hot air (right).

3.4.3 Awards

The following awards were obtained in Year 4 for the SolPol research project:

- **Energy Globe Oberösterreich 2018** (Honory Award winner – Category "Fire", 21.03.2018)
- **Energy Globe Austria 2018** (Nominee – Category "Sustainable Plastics", 05.06.2018)
- **Österreichischer Solarpreis 2018** (Award winner, 29.09.2018)
- **Sustainability Award 2018** (Award winner – Category "Regional Cooperation", 07.06.2018)

4 Outlook

Over the last decade and particularly also since the project start, significant changes of market conditions for solar-thermal collector systems have evolved. For pumped solar-thermal systems in Austria and Europe there is now fierce competition by other renewable technologies providing thermal services such as for example PV / heat pump combinations. On the other hand, as the worldwide market analysis has revealed there is a huge market for very low-cost and extremely low-cost solar-thermal systems in low-income and middle-income countries.

The expertise and knowledge generated by *SolPol-4/5*, in addition to being utilized in commercial product lines building on and corresponding to the model solar systems of the work packages WP-01 and WP-02, reaches into numerous potential new application fields. This is particularly also driven by the fundamental know-how and achievements generated in work package WP-03, which led to significant performance enhancements in terms of upper service temperatures and long-term durability. To exemplify these new application fields, the following may be listed:

- Water storage liner materials for scalable heat stores based on novel polyolefins and offering extraordinary flexibility in design (reference can be made here to the FFG flagship project giga_TES, which started 01/2018 and in which several *SolPol-4/5* partners are involved).
- There seems to be a huge market for extremely low-cost non-pumped solar-thermal systems. If a market price of around $ 100 per system (hot water generation) can be achieved. Based on the *SolPol-4/5* research such market price goals may indeed be feasible.
- A further field deserving more attention are processing technologies, especially those, which directly require hot water. Here, recycling processes of plastics waste may serve as an example, in which the cleaning of the shredded plastics waste in hot water processes (ca. 70°C) is a crucial process step.

The project partners of *SolPol-4/5* will further explore these and other potential application fields (incl. non solar-thermal application fields) to make use and build upon the generated expertise and are determined to continue the research collaboration in future projects.

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Academic Theses (23)

PhD theses (**5**):

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- Gnong Wolfgang (PhD thesis, JKU-CTO, finished 2018)
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- Maringer Leila (PhD thesis, JKU-IAC, finished 2017)
- Neuhofer Sandra (PhD thesis, JKU-CTO, finished 2018)

MSc theses (**12**):

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- Altmann Josef (Master thesis, JKU-IPMT, finished 2018)
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- Kramer Hans (Master thesis, AEE INTEC, finished 2016)
- Krinner Wolfgang. (Master thesis, FH-Joanneum Kapfenberg, finished 2016)
- Pohn Bernhard (Master thesis, JKU-IPMT, ongoing)
- Saberi Iman (Master thesis, JKU-IPMT, finished 2017)
- Schellander David. (Master thesis, UFG-ID, finished 2016)
- Svitil Katharina (Master thesis, JKU-IPMT, finished 2018)

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- Leitl Alexander (Bahelor thesis, JKU-IPMT, finished 2015)
- Puffer Reinhard (Bachelor thesis, JKU-IPMT, finished 2014)
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- *"Novel Solar-Thermal Systems Based on Polymeric Materials - A Comprehensive Science-Driven Research Effort",* R.W. Lang, International Conference on Environmental Sustainability, Development, and Protection 2016 (ICESDP'16), Prague (CZE), International ASET Inc., Paper ID: 108, (2016)
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- *„Material Properties of Plastics for Solar-Thermal Collector Mounting Systems"*, J. Fischer, P. Bradler, R.W. Lang, S. Leitner, G.M. Wallner, Proceedings ISES Solar World Congress 2017, 1993-1999 (doi: 10.18086/swc.2017.31.02) (2017)
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- *„Investigations on the distribution of polymer additives in polypropylene using confocal fluorescence microscopy"*, L. Maringer, M. Grabmann, M. Muik, D. Nitsche, C. Romanin, G.M. Wallner, W. Buchberger, International Journal of Polymer Analysis and Characterization, 1-7 (doi: 10.1080/102366X.2017.1367120) (2017)
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- *„Effect of beta-nucleation on aging and crack growth resistance of polypropylene exposed to chlorinated water"*, J. Fischer, P. Freudenthaler, P. Bradler, R.W. Lang, S.C. Mantell, Proccedings 19th Plastic Pipes Conference, 10 pages (2018)
- *„Characterization of Irradiation Crosslinked Polyamides for Solar Thermal Applications – Basic Thermo-Analytical and Mechanical Properties"*, P. Bradler, J. Fischer, G.M. Wallner, R.W. Lang, Polymers 10, 969, 11 pages. (doi: 10.3390/polym10090969) (2018)
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- Gleisdorf Solar 2014, 25.-27.06.2014, Gleisdorf (A):
  - *"Entwicklung eines Kunststoffkollektors mit eigensicherer Temperaturbegrenzung im Rahmen von SolPol-2 / AP-01"*, A. Thür, UIBK Innsbruck
  - *"Die österreichische Solarthermie-Forschungsinitiative SolPol im Kontext der Energiewende"* R.W. Lang, G.M. Wallner, JKU Linz
  - *"Materialtechnologisch getriebene Gestaltungsmethoden: Kollektorentwicklung im interdisziplinären Umfeld",* F. Nimmervoll, University of Art Linz
  - *"Neuartige Polyolefine für solarthermische Absorber"*, M. Povacz, G.M. Wallner, R.W. Lang, JKU Linz – <u>*Best Poster Award*</u>
  - "*The Austrian Solarthermal Research Initiative SolPol in the Context of the Energy Transition",* R.W. Lang, JKU Linz
  - *"Neuartige Polyolefine für solarthermische Absorber"*, S. Beißmann, W. Buchberger, R.W. Lang, M. Povacz, G.M. Wallner, JKU Linz (Poster)

- 24. Symposium Thermische Solarenergie, 07-09.05.2014, Bad Staffelstein (D):
  - *"Ein Beitrag zur Simulation und Messung eines Kunststoffkollektors mit integriertem Überhitzungsschutz",* C. Hintringer, UIBK Innsbruck
  - *"Validierung und Anwendung eines Kollektorrechenmodells zur Entwicklung eines Kunststoffkollektors mit eigensicherer Temperaturbegrenzung",* A. Thür, UIBK Innsbruck
  - *"Neuartige Polyolefine für solarthermische Absorber und Wärmespeicher"*, G.M. Wallner, JKU Linz
  - *"Solarthermische Modellkollektoren und Kollektorkonzepte in Kunststoff- und Hybridbauweise"*, G.M. Wallner, JKU Linz
  - "*Novel polyolefins for solarthermal absorbers and heat storages",* G.M. Wallner, K. Grabmayer, M. Povacz, R.W. Lang, JKU Linz
  - *"Solarthermische Systeme aus Polymerwerkstoffen: SolPol-1/2",* J. Fischer, R.W. Lang, G.M. Wallner, JKU Linz
  - *"Polyolefin materials for solarthermal absorbers and heat storages"*, S. Beißmann, W. Buchberger, K. Grabmayer, R.W. Lang, M. Povacz, G.M. Wallner, JKU Linz (Poster)
- EuroSun 2014, 16.-19.09.2014, Aix-les-Bains (F):
  - *"Collector Efficiency Calculation Tool for the Plastic Collectors with Temperature Limitation"*, paper ID: 89147, A. Thür, UIBK Innsbruck
- 10th International Conference on Geosynthetics, 21.-24.09.2014, Berlin (D):
  - *"High temperature resistant geomembranes for hot brine "*, M. Haager, AGRU
- SHC 2014, 13.10.2014, Beijing (VRC):
  - *"Polymer based solarthermal collectors - Collector designs, requirements for absorber materials and lifetime prediction"*, G.M. Wallner, R.W. Lang, M. Povacz, K.J. Geretschläger, R. Hausner, A. Thür, JKU Linz, AEE INTEC, UIBK-EEB
  - *"Tailor-made polymeric materials for collectors and heat storages"*, G.M. Wallner, JKU Linz
- SHC – International Conference on Solar Heating and Cooling for Buildings and Industry 2015, 02.-04.12.2015, Istanbul (TUR):
  - *"Polymeric materials in solar-thermal systems - Performance requirements and loads",* T. Ramschak, R. Hausner, C. Fink, oral presentation, AEE INTEC
  - *"Novel Solar Thermal Collector Systems in Polymer Design – Part 3: Aging Behavior of PP Absorber Materials",* M. Povacz, G.M. Wallner, M. Grabmann, S. Beißmann, K. Grabmayer, W. Buchberger, R.W. Lang, oral presentation, JKU-IPMT
  - *"Novel Solar Thermal Collector Systems in Polymer Design – Part 5: Fatigue characterization of engineering PA grades for pressurized integrated storage collectors",* Fischer, J., Bradler, P.R., Schlaeger, M., Wallner, G.M., Lang, R.W., oral presentation, JKU-IPMT
  - *"Novel Solar Thermal Collector Systems in Polymer Design - Part 2: Development, Durability and Lifetime Assessment of PP Absorber Materials for Overheating Controlled Flat-Plate Collectors",* M. Grabmann, M. Povacz, G.M. Wallner, R.W. Lang, poster presentation, JKU-IPMT
- Macromolecular Colloquium Freiburg 2016, 24.-26.02.2016, Universität Freiburg (D):
  - *"Energy Transition and the Key Role of Polymeric Materials",* R.W. Lang, JKU-IPMT
- International Conference on Environmental Sustainability, Development, and Protection 2016 (ICESDP'16), 30.-31.03.2016, Prague (CZE):
  - *"Novel Solar-Thermal Systems Based on Polymeric Materials - A Comprehensive Science-Driven Research Effort",* R.W. Lang, JKU-IPMT
- 26. Symposium Thermische Solarenergie, 20.-22.04.2016, Bad Staffelstein (D):

- *"Temperaturbegrenzung für Kunststoffkollektoren durch Durchlüftung",* T. Ramschak, R. Hausner, C. Fink, AEE INTEC

- 6th Bratislava Young Polymer Scientists workshop (BYPos) 2016, March 14-18, High Tatras:
  - *"Melamine based stabilizers"*, S. Neuhofer, lecture
- Re-source 2016: Resourcenschonung – von der Idee zum Handeln, 21.04.-22.04.16, München (GER):
  - *"Kunststoffe im Kontext von Sustainable Development", R.W. Lang, JKU-IPMT*
- 3rd International Conference on Bio-based Polymers and Composites (BiCoPo), 28.8.-1.9.2016, Szeged:
  - *"Cellulose nanocrystals used for immobilization of polymer antioxidants"*, lecture, S. Neuhofer, JKU-CTO
- MoDeSt Conference 2016, 4.-8.9.2016, Cracow (POL):
  - *"Melamine based additives, Modification, Degradation and Stabilization (MoDeSt"),* lecture, S. Neuhofer, JKU-CTO
- Gleisdorf Solar 2016, 08.-10.06.2016, Gleisdorf (AUT):
  - *"Räumliche Simulation von Druck-beaufschlagten Folienabsorbern und deren Faltenbildung",* Proceedings, Paper submitted, F. Nimmervoll, J. Kaindlstorfer, UFG-ID
  - *„Compact heat – Fortschritte bei gepumpten Solarthermieanlagen durch Industriedesign",* Proceedings, Paper submitted, D. Schellander, F. Nimmervoll, G.M. Wallner, UFG-ID
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  - *„Temperaturbegrenzung für Kunstoffkollektoren durch Durchlüftung",* Proceedings and Poster, T. Ramschak, R. Hausner, C. Fink, AEE INTEC
  - *"Praktische Erfahrungen (Teil 2) - Temperaturbegrenzung für Kunststoffkollektoren durch Durchlüftung",* Proceedings, Poster, T. Ramschak, R. Hausner, C. Fink, AEE INTEC; H. Poscharnig, GREENoneTEC
- Plastics Pipes XVIII Conference 2016, 12.-14.09.2016, Berlin (GER):
  - *"Fatigue crack growth resistance of polypropylene in chlorinated water at different temperatures",* J. Fischer, P.R. Bradler, R.W. Lang, G.M. Wallner, oral presentation, JKU-IPMT
  - *"A Novel Procedure for Characterizing Fatigue Crack Growth"*, J. Fischer, P.J. Freudenthaler, P.R Bradler, R.W. Lang, poster presentation, JKU-IPMT
- 11th ISES EuroSun Conference, 11.-14.10.2016, Palma de Mallorca (ESP):
  - *"Global aging and lifetime prediction of polymeric materials for solar thermal systems – Part 2: Polyamide 66 glass fiber reinforced absorbers for integrated storage collectors",* oral presentation, P.R. Bradler, JKU-IPMT
  - *"A Fracture Mechanics Based Lifetime Assessment Approach for Polyamide used for Integrated Storage Collectors",* poster presentation, P.R. Bradler, JKU-IPMT
  - *"Global Aging and Lifetime Prediction of Polymeric Materials for Solar Thermal Systems – Part 3: Polyolefin Liners for Heat Storages",* oral presentation, M. Grabmann, JKU-IPMT
  - *"Global Aging and Lifetime Prediction of Polymeric Materials for Solar Thermal Systems – Part 1: Polypropylene Absorbers for pumped Systems",* poster presentation, M. Grabmann, JKU-IPMT
- BALEWARE 2016: Sustainable Energy and Clean Water, 11.-13.12.2016 NM-AIST, Arusha, Tanzania:
  - *"Renewable energy and water for the world: A challenge and opportunity for polymer science and the polymer industry",* R.W. Lang, JKU-IPMT
  - *"Eco-Efficiency of Polymer-Based Solar-Thermal Collectors",* oral presentation, M. Gall, JKU-IPMT
- IdentiPlast 2017 - 13th International Conference on the Recycling & Recovery of Plastics, 22.02.2017, Vienna (AUT):

- *"The role of resource efficiency and eco-innovation for a Sustainable Circular Economy of Plastic", oral presentation,* R.W. Lang, JKU-IPMT

- Fachtagung "Kunstoffe für die Umwelttechnik – Abluft- und Rauchgasreinigung im Fokus", 04.04.2017, Bad Hall (AUT):
  - *"Polymerwerkstoffe für regenerative Energie/Stoff-Technologien", oral presentation,* R.W. Lang, JKU-IPMT
- GOECH-Colloquium, University of Innsbruck, 29.05.2017, Innsbruck (AUT):
  - *"Global Change and Challenges – Role and Contribution of Polymeric Materials", oral presentation,* R.W. Lang, JKU-IPMT
- 27. Symposium Thermische Solarenergie 2017, Bad Staffelstein (GER):
  - *„Praktische Erfahrungen (Teil 2) - Temperaturbegrenzung für Kunststoffkollektoren durch Durchlüftung"*, T. Ramschak, F. Veynandt, R. Hausner, C. Fink
- Eurosun 2018 Conference, Rapperswil (CHE):
  - *„Polymer Collectors - Temperature Control Thermosyphon Valve Development and System Integration"*, A. Thür, J. Schroll, N. Hauer
- „28. Symposium Thermische Solarenergie 2018, Bad Staffelstein (GER):
  - *Speicherkollektoren –Systementwicklung auf Basis von Polymermaterialien"*, T. Ramschak, F. Veynandt, C. Fink, H. Poscharnig

Other Publications

- European patent: „Verfahren zur elektrochemischen Herstellung spektral selektiver Absorberschichten auf einem Aluminiumsubstrat" (EP2818584), Calus
- Österreichische Energieagentur, 05.06.2014, Wien (A):
  - *"Kunststoffe als Schlüsselwerkstoffe und Motor der Energiewende"*, lecture by R.W. Lang, JKU Linz
- *"Sonnenkollektoren aus Plastik",* in: die Presse, 06.09.2014 also online publication, 05.09.2014
- 35 Jahre Haidlmair: Symposium und Tag der offenen Tür, 11.09.2014, Nussbach (A):
  - *"Kunststoffe – Eine Werkstoffklasse verändert die Welt",* lecture by R.W. Lang, JKU Linz
- SHC Task Definition Workshop Solar Heating and Cooling, 15.09.2014, Freiburg/Breisgau (D):
  - *"Cost-efficient plastics for solar-thermal systems",* lecture by G.M. Wallner, JKU Linz
  - *"Price reduction of solar-thermal systems",* lecture by A. Thür, UIBK-EEB
- 18th IEA SHC Task39 Meeting, 30.09.2014, Oslo (N):
  - *"Polymeric materials for solarthermal applications",* lecture by G.M. Wallner, JKU Linz
- *"Energiewende – die Rolle der Kunststoffe",* in: chemie&more 05.14, 10.2014
- Solarenergie und Kunststoff – Von der Vision zur Innovation, 29.10.2014, Wels (A):
  - *"Die Rolle der Kunststoffe für die Nutzung von Solarenergie*", lecture by R.W. Lang, JKU Linz"
- Kunststoff = Schlüsselwerkstoff der Zukunft, 20.11.2014, Bad Hall (A):
  - *"Kunststoffe für Erneuerbare Energien – Chancen und Möglichkeiten",* lecture by R.W. Lang, JKU Linz
- Open house day, University of Art Linz: Presentation of research activities *SolPol-4/5*; 24.04.2015; Linz (A), F. Nimmervoll, E. Bachlmair
- IEA SHC Task 54 – 1st Experts Meeting, 21.-22.10.2015, Freiburg (D):
  - *"Introduction to Subtask C: Objectives, content and schedule",* oral presentation, G.M. Wallner, JKU-IPMT

- Oral presentation, T. Ramschak, AEE INTEC

- Braumann, J., Nimmervoll, F., Lange Nacht der Forschung 2016
- IEA SHC Task 54 – 2nd Experts Meeting, 03.-04.05.2016, Florence (I):
  - *“Cost assessment and reduction potentials for pumped solar thermal hot water systems“,* oral presentation, R. Buchinger, Sunlumo
  - *“Novel materials – Loading conditions for pumped hot water systems“,* oral presentation, T. Ramschak, AEE INTEC
  - *“Potential components for solar-thermal systems from other industrial sectors“,* oral presentation, A. Thuer, UIBK-EEB
  - *“Novel materials – Screening and assessment on specimen level“, G.M. Wallner,* oral presentation, JKU-IPMT
  - “Aging Behavior of Polypropylene Absorber Materials for Hot Water Collectors”, oral presentation, G.M. Wallner, M. Grabmann, JKU-IPMT
- Lenzing, Austrian patent: „Verfahren zur Herstellung eines Wärmeübertragungselements (A2016/50135-AT-00)“
- Gleisdorf Solar 2016, 9.6.2016 at AEE INTEC:
  - *„Lebensdauervorhersage für Kunststoff-Flach- und Speicherkollektoren“*, Poster presentation, G.M. Wallner, JKU-IPMT
- *Polymer Degradation Discussion Group (PDDG), 30.08-03.09.2016, Stockholm (S):*
  - *“Antioxidant based on Melamine/Phenol derivatives”,* poster presentation, S. Neuhofer, JKU-CTO
- *“Sustainable Development, Energy Transition and the Key Role of Polymeric Materials”, Hong Kong University of Science* and Technology HKG (CHN),17.09.2016, oral presentation, R.W. Lang, JKU-*IPMT*
- *“Polymeric Materials & Sustainable Development - A Challenge & Opportunity for Polymer Science and the Polymer Industry”, BASF Advanced Materials and Systems, 23.09.2016, Pudong, Shanghai (CHN), oral presentation, R.W. Lang, JKU-IPMT*
- Vergabe der Österreichischen Solarpreise 2016 durch EUROSOLAR AUSTRIA, 01.10.16, Wien (A):
  - *“Materialforschung für die Energiewende – Österreichische Praxisbeispiele und Empfehlungen für die Politik“,* oral presentation, R.W. Lang, JKU-IPMT
- IEA SHC Task 54 – 3rd Experts Meeting, 06.-07.10.2016, Stuttgart (GER):
  - *“Info sheet on cost reduction methods in other industries“,* oral presentation, A. Thuer, UIBK
  - *“Cost reduction in other industries - Case study impellers“,* oral presentation, K. Schnetzinger, APC
  - *“Loading conditions for integrated storage collectors“,* oral presentation, T. Ramschak, AEE INTEC
  - *“Aliphatic vs. aromatic polyamides for ICS“,*oral presentation, M. Grabmann, JKU-IPMT
  - “Components for easy-to-install solar thermal hot water systems”, oral presentation, R. Buchinger, Sunlumo
  - *“Global Aging and Lifetime Prediction of Polyamid 66 Glass-fiber Reinforced Absorbers for Integrated Storage Collectors”,* M. Grabmann, oral presentation
- SolPol press conference, 11.10.16 Vienna (AUT)
- Presentations at the Plastics K-fare 2016, 19.10.-26.10.16, Düsseldorf (GER):
  - *“Sustainable Development and Academic Education & Research”,* oral presentation, R.W. Lang, JKU-IPMT
  - *“Diskussionsrunde “Ressourceneffizienz,”* moderation, R.W. Lang, JKU-IPMT
  - *„Plastics for Photovoltaics – A Contribution tot he Energy Transition“,* oral presentation, M. Gall, JKU-IPMT

- *"Anti-Aging for Polymers – A Contribution to Resource Efficiency",* speed talk, S. Neuhofer, JKU_CTO

- Adacemic Lecture Series *"Solar-Technologies for Sustainable Development":*
  - Johannes Kepler University Linz, summer semester 2014
  - University of Bayreuth, summer school 2014
  - University of Freiburg, winter semester 2014/2015
  - Johannes Kepler University Linz, summer semester 2015
  - University of Bayreuth, summer school 2015
  - University of Freiburg, winter semester 2015/2016
  - Johannes Kepler University Linz, winter semester 2016
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  - University of Freiburg, winter semester 2016/2017
  - Johannes Kepler University Linz, summer semester 2017
  - University of Bayreuth, summer school 2017
  - University of Freiburg, winter semester 2017/2018
- *"Sustainable Development in Context – The Nexus to Technologies & Materials Part 1: Introduction, Scope and Aims"*, Burkina Faso, Ouagadougou, 27.02.2017, International Institute for Water and Enviromental Enginneering, oral presentation, R.W. Lang, JKU-IPMT
- *"Sustainable Development in Context – The Nexus to Technologies & Materials Part 2: Sustainable Development and the Nexus to Technologies & Education",* Burkina Faso, Ouagadougou, 28.02.2017, International Institute for Water and Enviromental Enginneering, oral presentation, R.W. Lang, JKU-IPMT
- *"Polymerwerkstoffe für Energieeffizienz und regenerative Energie/Stoff-Technologien",* Werkstoffe und Materialien für die Energiewende, acatech Materiealien, published 2017, R.W. Lang, JKU-IPMT
- *"Effect of various stabilizer systems for glass-fiber reinforced polyamide on the fatigue crack growth resistance",* 27.04.2017, Master thesis presentation, B. Pohn, JKU-IPMT
- IEA SHC Task 54 – 4th Expert Meeting, 03.-04.05.2017, Rapperswil (CHE):
  - *"High throuput screening of PA-materials for ICS",* oral presentation, P.R. Bradler, JKU-IPMT
- *„Potentiale zur Optimierung solarthermischer Anlagen. Mehrwert, Nutzungsattraktivität und Wirtschaftlichkeit*", Masterarbeit an der Studienrichtung Industrial Design, Institut für Raum und Design, D. Schellander, UFG-ID
- *„Alterungsverhalten von Carbon Nanotube-pigmentierten Polypropylen-Werkstoffen"*, C. Klocker, Master's thesis presentation, 2016, March 15, JKU-IPMT, Linz (AUT)
- ESIS TC04 Conference 2017, September 10-14, Les Diablerets (CHE):
  - *„Effect of stabilization systems for glass fiber reinforced polyamides on the fatigue crack growth resistance under superimposed environmental loads"*, P. Bradler, J. Fischer, G.M. Wallner, R.W. Lang, poster
- AEM Conference 2017, September 11-13, Surrey (UK):
  - *„Effect of Irradiation induced cross-linking on the Properties of different Polyamide Grades"*, P. Bradler, J. Fischer, G.M. Wallner, R.W. Lang, poster
  - *„Effect of thickness and temperature on the aging behaviour of polypropylene random copolymers for seasonal heat storages"*, G.M. Wallner, M. Grabmann, K. Grabmayer, W. Buchberger, D. Nitsche, poster
- SHC Conference 2017, October 29 – November 2, Abu Dhabi (UAE):
  - *„Aging Behaviour of Polypropylene solar thermal absorber materials with carbon nanotube pigmentation"*, G.M. Wallner, M. Grabmann, C. Klocker, W. Buchberger, D. Nitsche, poster

- *„Effect of aging in hot chlorinated water on the mechanical behavior of polypropylene for solar-thermal applications"*, J. Fischer, S.C. Mantell, P. Bradler, G.M. Wallner, R.W. Lang, poster

6 Contact

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