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Novel Solar-Thermal Systems Based on Polymeric Materials: A Comprehensive Science-Driven Research Effort

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1. Introduction and Scope

Considering the huge but as yet unlocked market potential for low-temperature heat, solar-thermal (ST) technologies are occasionally referred to as "sleeping giant" (Stryi-Hipp et al., 2012). Today ST systems are mainly used for domestic hot water (DHW) heating and solar assisted space heating (SH). For such applications the desired temperature levels of the system are up to 95°C. Regarding ST systems configurations, in Europe, USA and Australia, pumped or forced circulation systems are mainly used. In contrast, in other world regions (especially China, Asia, Latin America, Sub-Saharan Africa) low-cost and low-comfort non-pumped systems of the thermosiphon type are usually applied. Besides other aspects, costs are still an important barrier for their broader deployment and market penetration. While non-pumped thermosiphon systems for DHW in their key markets are often in use without any alternatives, pumped systems in industrialized countries have to compete with other heating supply technologies (usually based on fossil fuels or electricity).

To reduce the costs of ST systems, research work in the last decade has focused on the development of novel collectors and storage tanks for pumped systems. One approach was to reduce the costs for collectors and storage tanks by the enhanced use of plastics instead of metals. This was also the main cause for implementing the *IEA SHC Task39* on *"Polymer Materials for Solar Heating Systems"*, which was established in 2006. In a collaborative effort of various research institutions and various company partners from up to 15 countries, the applicability of polymeric materials and the related innovation potential of ST systems and components was investigated using an interdisciplinary approach (network of experts in solar-thermal engineering and in polymer technologies). In *Task39* the state of the art of polymeric materials in ST systems was explored in a comprehensive manner. An overview of the results achieved is provided elsewhere (Wallner and Lang, 2006; Burch, 2006; Meir et al., 2008; Kaiser et al., 2012; Köhl et al., 2012; Lang and Wallner, 2012; Reiter et al., 2012; Wallner et al., 2012).

In *IEA SHC Task39* the state of the art on polymeric materials for solar-thermal technologies was continuously updated. While previous research work in the United States (e.g., Burch, 2006; Burch and Thornton, 2006; Kearney et al., 2005; Rhodes, 2006; Roberts et al., 2000; Wu et al., 2004) was of high relevance for *IEA SHC Task39*, significant advances were achieved more recently mainly in Europe (incl. Israel). In addition to polymer based unglazed swimming pool collectors, which dominate in this market, polymer based collectors for pumped and non-pumped systems were also introduced for DHW supply. Furthermore, various types of storage tanks with main components made from plastics were commercialized in the last decade (Köhl et al., 2012).

And yet, although in recent years there is a clear tendency for an increased use of polymeric materials in ST collector systems for low-temperature heat supply (up to 95 °C), only few polymeric collector systems are currently commercially available and installed. Moreover, the application of polymer collectors so far is limited to certain regions (e.g., Australia, America, Israel, United Kingdom, and Norway) and rather negligible market shares (Meir et al., 2008; Mauthner et al., 2015). Considering the need for further cost reductions of ST systems, it is increasingly recognized, however, that substantial research and development efforts still need to be and should be undertaken to exploit the potential of polymeric materials for such applications and to achieve broader market acceptance.

Recognizing the tremendous potential in the solar-thermal field for polymer-driven technological innovations that may positively affect the cost/performance ratio as a prime pre-requisite for broad market acceptance, as of 2009 a science-driven multi-lateral research project platform was established at the Johannes Kepler University (JKU) of Linz/Austria under the acronym *SolPol* (*Solar Energy Systems based on Polymeric Materials)*. Some of the main characteristics and features of *SolPol* research projects include:

- *Mid- and long-term collaboration* of partners from *academic-scientific and other research institutions* with *industrial partners*, both groups covering the entire value creation chain.
- Effective use of financial resources (funding budgets) through multi-partner participation and *excellent leverage in terms of cost coverage* by individual partners (leverage factors of 5 to 40!).
- *Strong role of scientific partners* acting *as initiator, coordinator and/or RTD partner, frequently* also assuming the *project management* function in close association with all partners.

A special focus of the *SolPol* research platform is on polymer based ST systems (Lang et al., 2013). Combining the polymer and solar-thermal energy research expertise of numerous scientific and industrial partners covering the entire value creation chain in the multi-lateral and longer-term research projects *SolPol-1/2* (duration 2009-20014) and *SolPol-4/5* (2014-2018) provided and still ensures an excellent frame and foundation for innovative ST technology developments. The positioning of the 9 scientific partners and the 14 industrial company partners of these SolPol projects along the value chain is illustrated in Fig. 1. As far as materials related research is concerned, the methodological approach of the research work reflects this value chain approach and is based on establishing appropriate material structure-property-processing-performance (msp³) relationships by applying most modern and advanced concepts of polymer science and engineering at each stage of the value chain. While the prime objectives of *SolPol-1/2* were in the development of novel material grades that could sustain the specific requirements of some key components of ST systems, the currently ongoing project *SolPol-4/5* aims at integrating these findings into the design, modelling, production and testing of totally novel all-plastics based collectors systems. The focus is on both, low-cost pumped systems and high-quality non-pumped integrated storage systems.

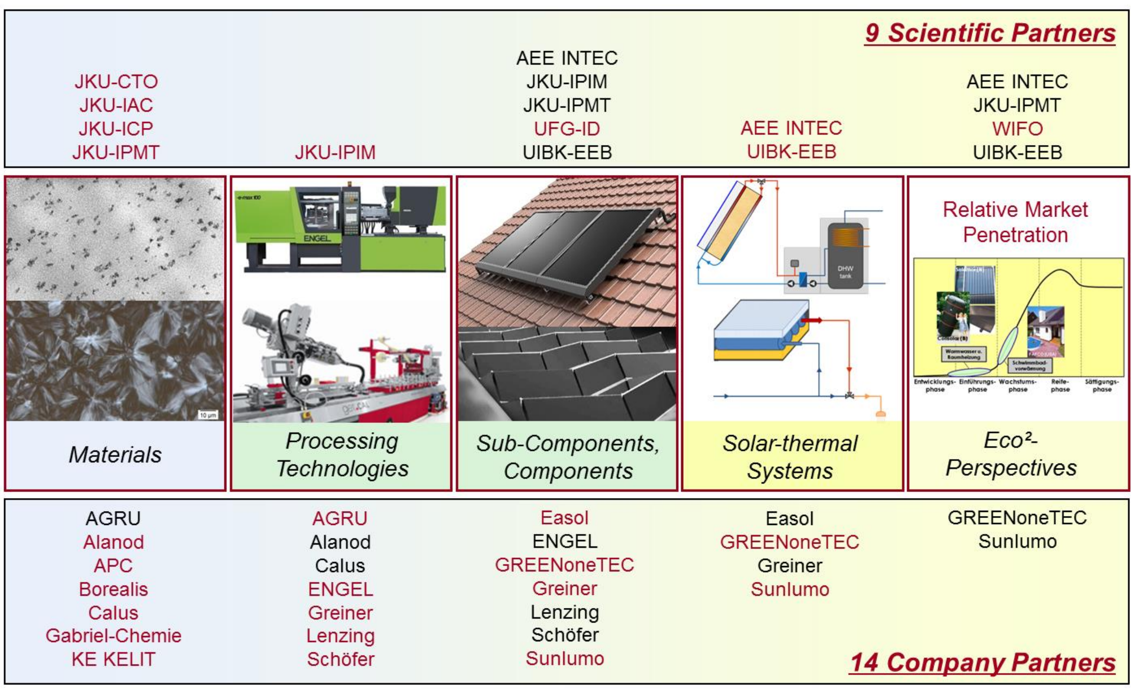


Fig. 1: Positioning of the research partners of SolPol-1/2 and SolPol-4/5 along the value creation chain towards all-polymeric solar-thermal collector systems (partner positioning in core competencies in red letters).

The present paper highlights and provides an overview of the methodological and scientific approach towards all-polymeric ST collector systems with a focus on scientific-technological results on service lifetime assessment for polymeric materials and components in ST systems and how this translates into levelized cost of heat calculations. Moreover, examples of successful industrial product development achievements are provided.

2. Overall Goals, Methodology and Approach

A prime objective of the *SolPol* initiative in ST polymer technology research is to provide a sound scientific foundation in support of the development of novel polymer-based ST systems by simultaneously achieving the following overall technical and economic goals:

- To conceptually develop, practically build, function-proof and evaluate highly polymer based, pumped collector model systems for DHW and SH applications in Europe and North America achieving systems costs reductions by about 50% (i.e., <500 €/m2) compared to current systems while offering an equivalent lifetime of at least 20 years.
- To develop novel non-pumped, integrated storage collector systems in all-polymeric or hybrid design for DHW preparation in subtropical 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.

From a polymer science viewpoint, the aspect of lifetime assessment - and in particular service-oriented lifetime assessment for existing and novel polymer compounds by a highly accelerated methodology - is of prime importance. Hence, this paper focuses on this latter topic, providing an overview of the general methodological approach along with selected results to exemplify the strength and validity of the approach. Moreover, based on the lifetime assessment results, first estimates of cost-of-heat will be provided for pumped polymer based ST model systems. To allow for a comprehensive, service-relevant methodological procedure, the polymer research approach rested on a detailed systems analysis on four levels of perspective, depicted in Fig. 2.Also indicated in Fig. 2 are essential elements and features at each of these levels.

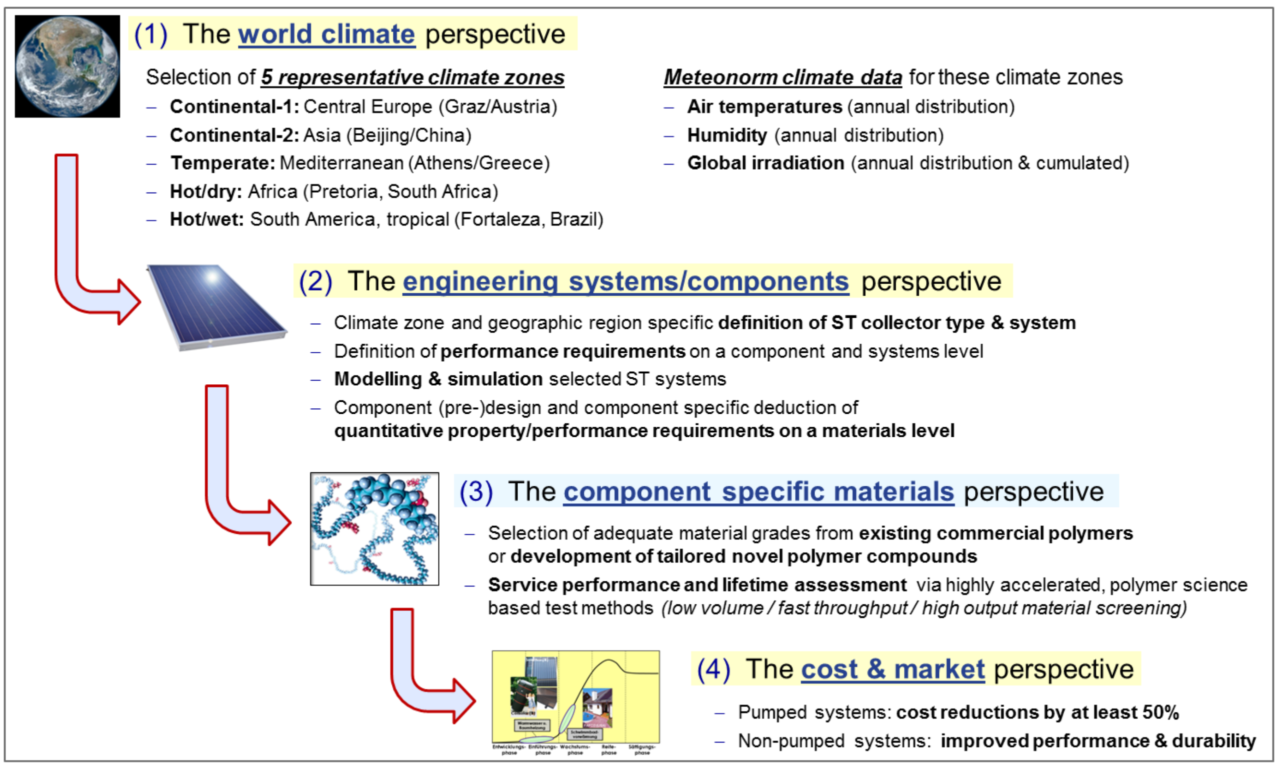


Fig. 2: Positioning of the research partners of SolPol-1/2 and SolPol-4/5 along the value creation chain towards all-polymeric solar-thermal collector systems (partner positioning in core competencies in red letters).

Starting from a *world climate* perspective, five representative climate zones with corresponding climate data for locations (cities) in these regions were initially selected (level (1) in Fig. 2). In a next step, climate zone and region specific collector types and systems were defined, for which component specific, quantitative material property/performance requirements were deduced via modelling and simulation (level (2) in Fig. 2). In total this included some 20 collector systems (Kaiser et al., 2012; Ramschak et al., 2015). Based on the property/performance requirements on a component and materials level, service lifetime investigations were performed with existing commercial and tailored novel polymer compounds, the novel compounds having also been developed as part of the *SolPol* projects (level (3) in Fig. 2). Taking the projected service lifetimes as evidence for achieving the above service life goals together with the ST systems cost goals (see overall technical and economic goals defined above), levelized cost of heat (LCOH) values may be calculated for region specific pumped and non-pumped ST systems (level (4) in Fig. 2).

3. Results and Discussion

As mentioned before, this paper includes key results to exemplify the comprehensive, systems-driven and polymer science based research approach towards all-polymeric ST systems, translating a world climate perspective into polymer performance requirements and service life assessment and further on to LCOH data. Further and more detailed aspects as to the results presented here are covered elsewhere (Kaiser et al., 2012; Lang et al., 2013; Povacz, 2014; Ramschak et al., 2015; Wallner et al, 2016).

Two examples for how key property requirements are deduced for specific ST systems components for pre-specified service applications are shown in Fig. 3. Example 1 refers to polyolefinic (PO) absorber for an overheating-controlled (OHC) pressurized collector system in the climate zone Continental-1(Graz/AT). Example 2 represents a PO liner for buried hot-water stores, as they are used quite commonly for example in Denmark and also in Germany (Köhl et al., 2012).

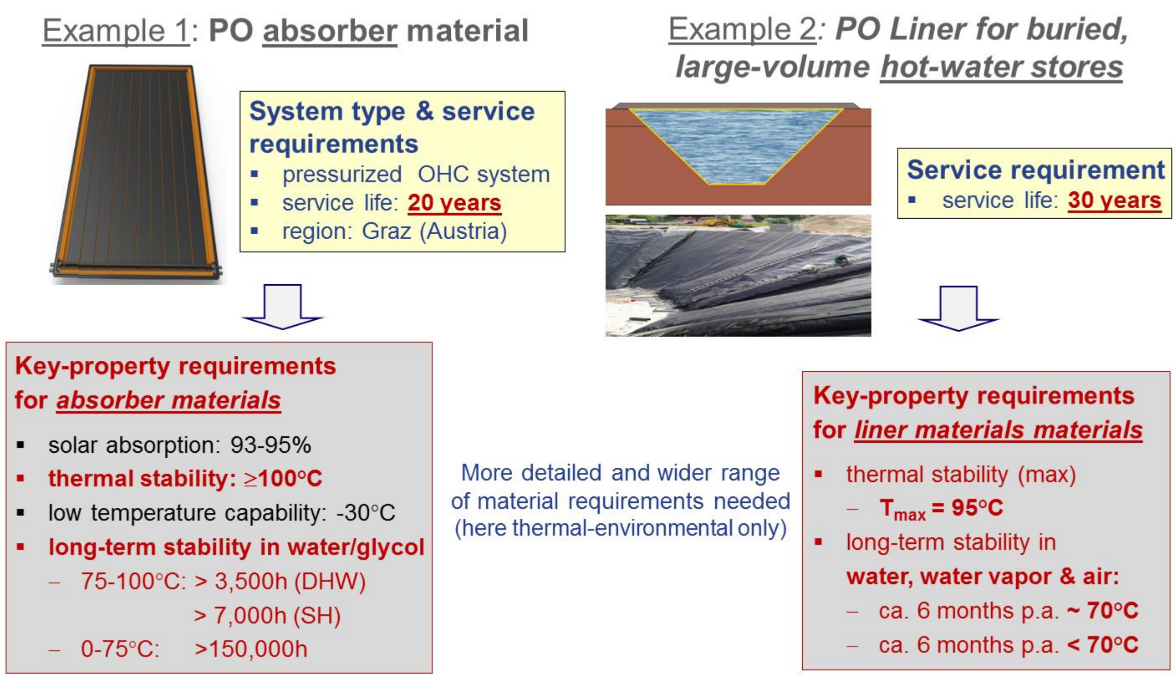
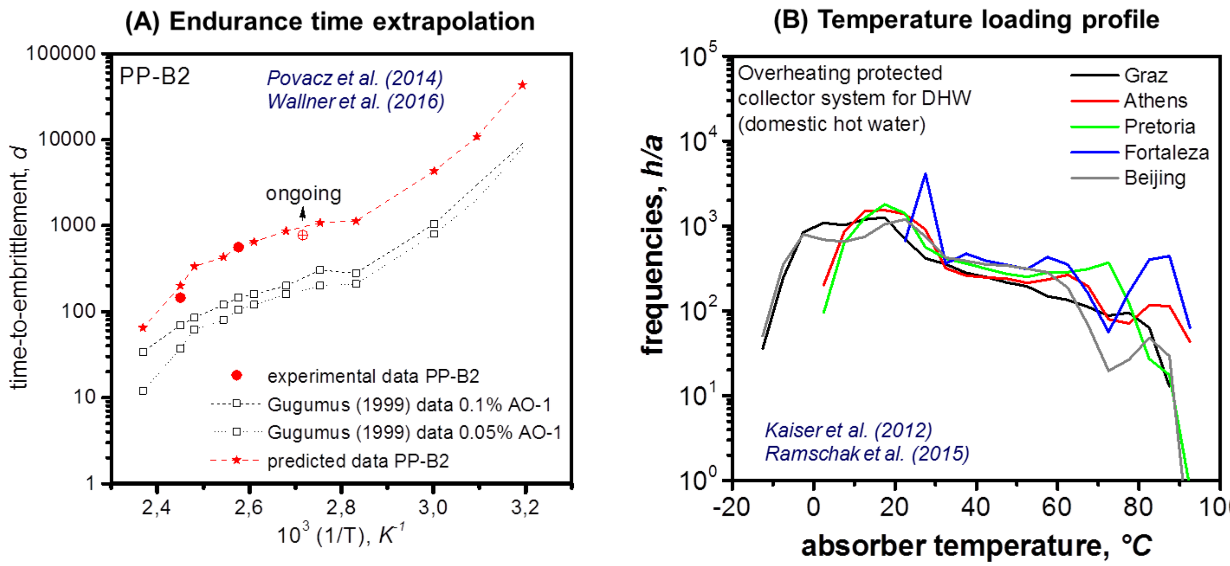


Fig. 3: Two examples of key performance and property requirements for specific ST systems components and pre-specified service applications.

While the key property requirements listed in Fig. 3 allow for a candidate material pre-selection, a more detailed analysis in terms of temperature profile along with more detailed requirements in terms of environmental and irradiation exposure over the required service life of a given component is usually needed. Moreover, to ensure a service life of 20 years as shown in Example 1 of Fig. 3 for the absorber, extensive investigations on the aging behaviour of a given material need to be performed along with a polymer science based model that allows for the transformation of accelerated shorter-term experimental results to long-term service behaviour.

Some quantitative results exemplifying such a procedure are shown in Fig. 4 for an absorber of an OHC domestic hot water collector (pumped system). First, to achieve embrittlement endurance times over a wide range of temperatures and as shown in Fig. 4A, an approach originally proposed by Gugumus (1991) was applied to highly accelerated experimental aging results (mechanical embrittlement in tensile experiments after exposure to selected environmental media at elevated temperatures) which were generated for various grades of polypropylene block-copolymers (PP-B). These data were then converged with annual temperature loading profiles for the absorber in the five representative world regions as deduced from collector systems simulations. Combining these data sets in Figs. 4A and 4B via a Miner's cumulative damage model provides the information as to expected calculated service lifetimes for the various world regions (see Fig. 4C). Also shown in a table in Fig. 4C is a comparison of calculated absorber service lifetimes for two different PP-B types when applied in the five representative world regions. Clearly, PP-B2 outperforms PP-B1, surpassing the service life requirement of 20 years for pumped systems in at least four of the world regions. In fact, as some of the aging experiments with PP-B2 are still ongoing (see Fig. 4A), the result for Fortaleza/BR may well also be positively affected once all aging data are available (i.e. for the present estimate, a conservative approach was taken for the material grade PP-B2).



(C) Lifetime modelling and assessment

- *extrapolation by Gugumus approach*
- *cumulative damage model (Miner's rule)*

*→ **failure time (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)	Graz/AT	Beijing/CN	Athens/GR	Pretoria/ZA	Fortaleza/BR
PP-B1	21	23	15	14	8
PP-B2	32	34	25	24	15

Povacz et al. (2014); Wallner et al. (2016)

Fig. 4: Service lifetime assessment of extruded polymer absorbers in pumped OHC-DHW collector systems; results for two grades of polypropylene block-copolymers (PP-B) exposed to region specific climate conditions (results for PP-B2 preliminary based on conservative assumptions).

Finally, assuming again a service life of 20 years for a polymer-based DHW pumped collector system with a reduction of overall systems costs by 50%, levelized cost of heat (LCOH) calculations were performed for various world regions, now even including climate data for further cities worldwide. The results are shown in Fig. 5, comparing LCOH data of polymer-based collector systems with current reference systems. Depending on the location, LCOH values for polymer based systems could potentially range from less than 3 €-cents/kWh (Antalya/Turkey) to just below than 6 €-cents/kWh (Graz/Austria). In other words, this analysis and these model calculations clearly reveal, that the cost competitiveness of polymeric ST systems also strongly depends on the geographical region.

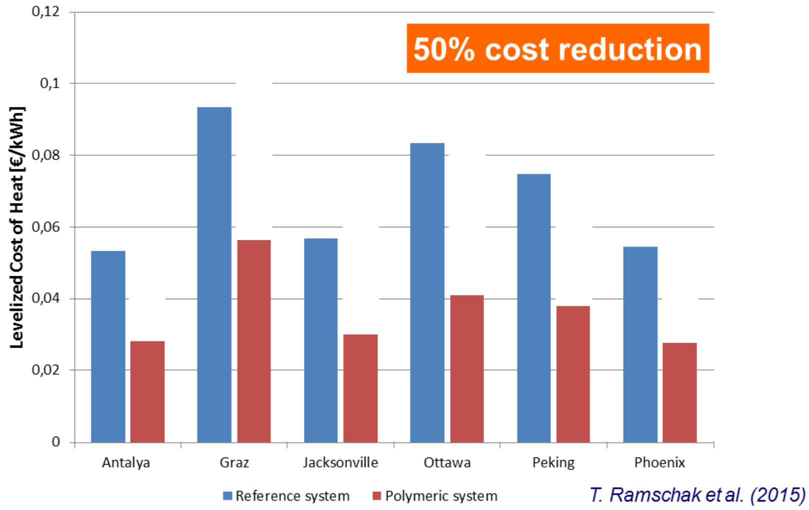


Fig. 5: Levelized cost of heat (LCOH) for typical reference collector systems vs. all-polymeric collector systems (various regions worldwide; pumped OHC-DHW system with a solar fraction of 70 %).

4. Summary and Conclusions

In this paper, a systematic approach towards developing novel polymer-based ST collector systems is presented, which to our knowledge for the first time breaks the world climate perspective down to the level of polymeric materials and the performance requirements for these materials and further on to region and ST system specific LCOH values. Thus, a unique tool is now available for supporting and guiding future research efforts towards the development of cost and performance competitive ST systems for various world regions.

Some key results achieved so far in context to this paper may be summarized as follows:

- A rather unique and comprehensive tool for defining required material property profiles on a specific component level based on collector systems definitions (e.g., reference, drainback and overheating controlled (OHC) collectors for DHW and SH-combi systems) and on climate data for various world and climate regions is now available.
- A set of accelerated methods for aging characterization of polymers in non-pressurized applications (based on micro-sized specimen and/or enhanced oxygen pressure) and pressurized applications (based on fracture mechanics concepts and cyclic crack growth experiments) has been developed and implemented.
- Novel pigmented polypropylene (PP) compounds with significantly improved aging behavior have been developed for absorber applications (black-pigmented) and back-cooler (white-pigmented) of OHC collectors.
- Novel polyolefin based liner materials with enhanced long-term stability (for seasonal storage tanks) have been developed and tested under highly accelerated lab conditions (screening tests).
- The feasibility of the back-cooling overheating control (OHC) principle in polymer collectors could be proven so that a cost-efficient way to limit the stagnation temperature of a polymeric collector to 95°C exists.
- Drainback collectors with stagnation temperatures up to 140°C at the absorber have been produced and tested with various engineering polymers (PA, PPA, sPS, PPS); however, more cost-efficient novel material grades (max. material costs of 6 €/kg) which are extrudable are needed to allow for overall systems cost reductions by 50%.
- Finally, some hybrid membranes were developed and shown to exhibit a high potential for various collector components (e.g., absorber, insulation). However, cost-efficient joining technologies have yet to be developed.

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