Sustainability Assessment of Most Relevant Solar Thermal Heat Systems

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Abstract

Solar thermal heat systems are of high relevance and interest for the supply of low temperature heat for different purposes. Especially, hot water systems are dominating the solar-thermal market with non-pumped systems gaining more and more importance. The main objective of this paper is to assess most relevant small and medium sized as well as large scale district solar-thermal heat systems as to their sustainable development metrics. While 2017 about 94% of the energy provided by solar thermal systems was used for domestic hot water, currently a trend to larger solar thermal systems with seasonal storage coupled to district heating networks is discernible. Solar thermal at present contributes about 1% to total heat consumption. The share of solar district heating and solar process heat applications is steadily increasing despite it is still only representing 3 % of the global market (Weiss and Spörk-Dür, 2018). The potential contribution is much larger. Many national governments seek to realize this potential by offering subsidies and feed-in-tariffs. Assessing sustainable development for solar thermal heat systems is a complex discipline. The best heat system depends to a large extend on the climate region. If solar heat is intermittent, seasonal, economic storage of heat is advantageous. Significant cost reductions of solar thermal systems and a shift towards polymeric materials to regain market growth and to improve ecological performance is required. For the assessment a 5-step methodology developed by Ashby et al. (2016) is used.

Keywords: thermal heat system; all-polymeric, sustainable development; assessment.

1. Introduction

Solar thermal heat systems are of high relevance and interest for the supply of low temperature heat for different purposes. Especially, hot water systems are dominating the solar-thermal market with non-pumped systems gaining more and more importance (Mauthner et al., 2016). Alternatives to the small hot water systems are medium-sized combi-systems allowing also for space heating or large systems for district heating and cooling or process heat. The current work is a follow-up of Kicker et al. 2017. The main objective of this paper is to assess most relevant solar-thermal heat systems as to their sustainable development metrics.

In recent years attempts have been made to open up a mass market for solar thermal energy and thereby promote the use of renewable energies with novel, more cost-effective materials and production processes. An alternative to metals is the use of cheaper plastics. Investigations showed that the use of proven methods of polymer processing can reduce the costs of manufacturing solar thermal systems by up to 50%. To assess the costs of the heat generated by solar thermal systems recently the levelized cost of heat (LCOH) evaluation procedure has been implemented. Buchinger [3] shows that LCOH for an all polymeric pumped flat plate collector system can go down to 2 €ct/kWhth. The LCOH for conventional, fossil oil based hot water preparation for a single family house (SFH) in Austria amounts to 10 €ct/kWhth. The LCOH for conventional, metal based, pumped flat plate collector systems for a single family house are ranging from 12 to 15 €ct/kWhth (Fischer, 2017). It is a clear fact all-polymeric solar thermal systems entail a high cost reduction potential for heat generation.

The holistic view of solar thermal systems in terms of sustainability opens up marketing possibilities of solar thermal heat systems based on novel all-polymeric materials.

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2. Methodology and approach

The much-quoted definition of sustainable development by the Brundtland Commission tells: 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (The Brundtland Report of the World Council on Economic Development, WCED 1987). But how is sustainable development to be achieved? The definition lacks of concrete guidance how to reach the goals.

Ashby et al. (2016) developed a 5-step analysis methodology for assessing sustainability of complex systems and multi-dimensional problems. The approach is to split the problem into layers and to follow a five-step strategy for assessing. The 5-step analysis includes:

1. the definition of the prime objective as well as the size and time scale,
2. the identification of the stakeholders,
3. the fact-finding step to research both the factual background of the articulations and the validity of the concern expressed by the stakeholder,
4. the synthesis of the facts for examination of how the facts influence human, natural and manufactured capital, and
5. the reflection step assessing the picture that has emerged and considering priority changes.

The current work is a follow-up of Kicker et al. 2017, where the focus was given to solar thermal systems for hot water preparation and the first three of the five above steps. In this paper the focus is to assess most relevant solar-thermal heat systems as to their sustainable development metrics. The range of investigated systems extends from systems for hot water preparation for single family houses, passing through hot water preparation for multifamily houses and small district heating up to large collector fields with seasonal storage for district heat providers. Step one, two and three are restated within this broader context.

3. Main results and conclusions

The layered approach to assess solar thermal collector systems as to their sustainable development metrics and the key findings are elucidated in the following.

3.1. Background information, prime objective and scale

To meet carbon-reduction targets heat generation from renewable sources is of utmost importance. Direct conversion of sunlight via solar thermal collectors has many attractions. Mean solar irradiance varies between 150 and 250 W/m^2 dependent on the world region. In the use phase, solar thermal systems emit negligible CO_2 and they reduce dependence on imported energy. Historically solar thermal has grown at 15% per year for the last 15 years. Worldwide a capacity of 410 GW_{th} was installed corresponding to a total of 586 million m^2 of collector area. The annual collector yield of water-based systems in operation by end of 2014 was about 1.2 exajouls saving about 0.1 gigatonnes of CO_2 (Mauthner et al., 2016). While 2014 about 94% of the energy provided by solar thermal systems was used for domestic hot water, currently a trend to larger solar thermal systems coupled to district heating networks is discernible (Weiss and Spörk-Dür, 2018). Solar thermal at present contributes about 1% to total heat consumption. The potential contribution is much larger. Many national governments seek to realize this potential by offering subsidies and feed-in-tariffs.

In Europe targets for a 20% reduction in carbon emissions by 2020 and an 80% reduction by 2050 were defined. To which extent are these targets achievable by solar thermal? Is it a sustainable development?

Solar heat is intermittent. Most of the solar heat is generated in summer. However, the heating demand is significantly higher in winter. Hence, seasonal storage of heat is required. Economic storage is work-in-progress, yet just rather limited available. Large-scale investment is required. Furthermore, a significant drop in the growth rates of solar thermal are discernible, especially in Europe. Hence, efforts are put on significant cost reductions of solar thermal systems to regain market growth. While solar thermal heat systems based on novel all-polymeric materials find their way to hot water preparation for single family houses, they are still not considered for application in large collector fields or applications for industrial process heat generation.

3.2. Stakeholders and their concerns

Contemporary news headlines suggest a range of stakeholders. Many current newslines are dealing with large systems. Only less can be found on the currently most important field of application which is domestic hot water preparation.

- “Drake Landing: A ray of sunshine for solar thermal energy”. Monty Kruger from CBC News posted that 2 or 3 sunny summer days are enough to heat homes throughout cold seasons in Alberta town`s solar community. (CBC News, February 14, 2016).
- “Gigantic Danish Solar Heating System Completed”. The world’s biggest solar heating system, completed in less than a year after signing the contract, consists of 156,694 m^2 of collectors and will provide 20% of the total heat consumption in Silkeborg. (Energy Supply, January 17, 2017).
- “Italy: new subsidy scheme for solar thermal up to 1000 m^2”. Large solar thermal plants will receive an incentive of 55 €/m^2 per year, over a period of 5 years. (solar district heating, February 6, 2013).
- “First Solar Civic Participation Project”. Crowdfunding participation model for solar thermal plants has reached €1.5 Mio. (EuroHeat&Power Industry News, November 2014).
- “Weltgrößter Solarspeicher soll Grazern einheizen”. Günter Pilch and Markus Zotter note that 20% of the district heating demand in Graz could be covered by solar thermal in 2019. (Kleine Zeitung, February 27, 2016).
- “ECREE begins move to exploit solar thermal energy potential in Ghana” The ECOWAS Center for Renewable Energy and Energy Efficiency (ECREE), has began processes to help Ghana exploit the abundant solar thermal energy potential for domestic and industrial use. (ghanaweb.com, September 26, 2017).
- “The sleeping giant is waking up” Bhoo Thirumalai, the Chief Executive Officer of Aspiration Energy and a solar aficionado, is a busy man these days. For years, the man who co-founded the successful IT company had been trying to rev it up with limited success. But suddenly things seem to be falling in place. (thehindubusinessline.com, August 29, 2017)
- “Clean Energy Isn’t Just the Future—It’s the Present” Solar power geysers to heat hot water sit on the roofs of a residential shack in the Alexandra township outside Johannesburg, South Africa (Bloomberg, April 19, 2017)

Based on these quotes and the value creation chain of the solar thermal industry the following key stakeholders are suggested:

- Government: Solar thermal could provide a contribution to meeting renewable energy commitments. Government has the power to make it happen through subsidies and feed-in tariffs.
- Heat providers: Solar thermal and large-scale storages allow for the substitution of economically inefficient fossil fuel co-generation plants with the by-product electricity, which is hard to sell economically due to the low electricity market prices.
- Heat system industry: Solar thermal is an interesting alternative in their product portfolio. Some of them already invested in collector manufacturing facilities.
- Collector makers: Many small- or medium-sized collector makers are on the market. Their profit margins are diminishing due to large enterprises established in China offering cheap products mainly for hot water preparation.
- Installers: Current system technologies for hot water preparation or space heating are not easy-to-install. More reliable system designs are needed for small-sized installers. Large-scale systems offer interesting market opportunities for more specialized companies.
- Property owners: They are attracted by subsidies. In some regions solar thermal systems allow for independent hot water supply and improvement in comfort (especially in less industrialized countries).
- NGOs: are campaigning for decentralized, renewable energy to halt climate change.
- R&D: Solar thermal is an attractive research field with open issues (e.g., thermal energy storage; function-oriented design and simulation of systems). Funding for research on solar thermal systems is stimulating.
- Investors: Crowdfunding initiatives are attracting general public. Large-scale systems are of interest for investors. To meet carbon-reduction targets heat generation from renewable sources is of utmost importance.

The relationship between the stakeholders for small and medium sized systems is displayed in Figure 1 reflecting also their specific influence / power and their interests. Figure 2 displays the shift of interest and influence of Heat Providers and Investors for large collector fields with seasonal storage by the example of district heat providers in Denmark.

Significant concerns for solar thermal heat is that this technology is in many cases to expensive. In contrast to photovoltaic power, there is still a lack of transparency and continuity regarding subsidies for solar thermal collector systems. Furthermore the intermittency of heat generation and the problem that heat storage is seen challenging, especially for domestic hot water systems with high performance collectors and poor performance storages. PV for hot water preparation (supplemented by heat pumps) is supposed by some as the smarter and cheaper solution and is a serious competitor especially in the small- and medium-size system segment for hot water preparation with or without combined space heating.

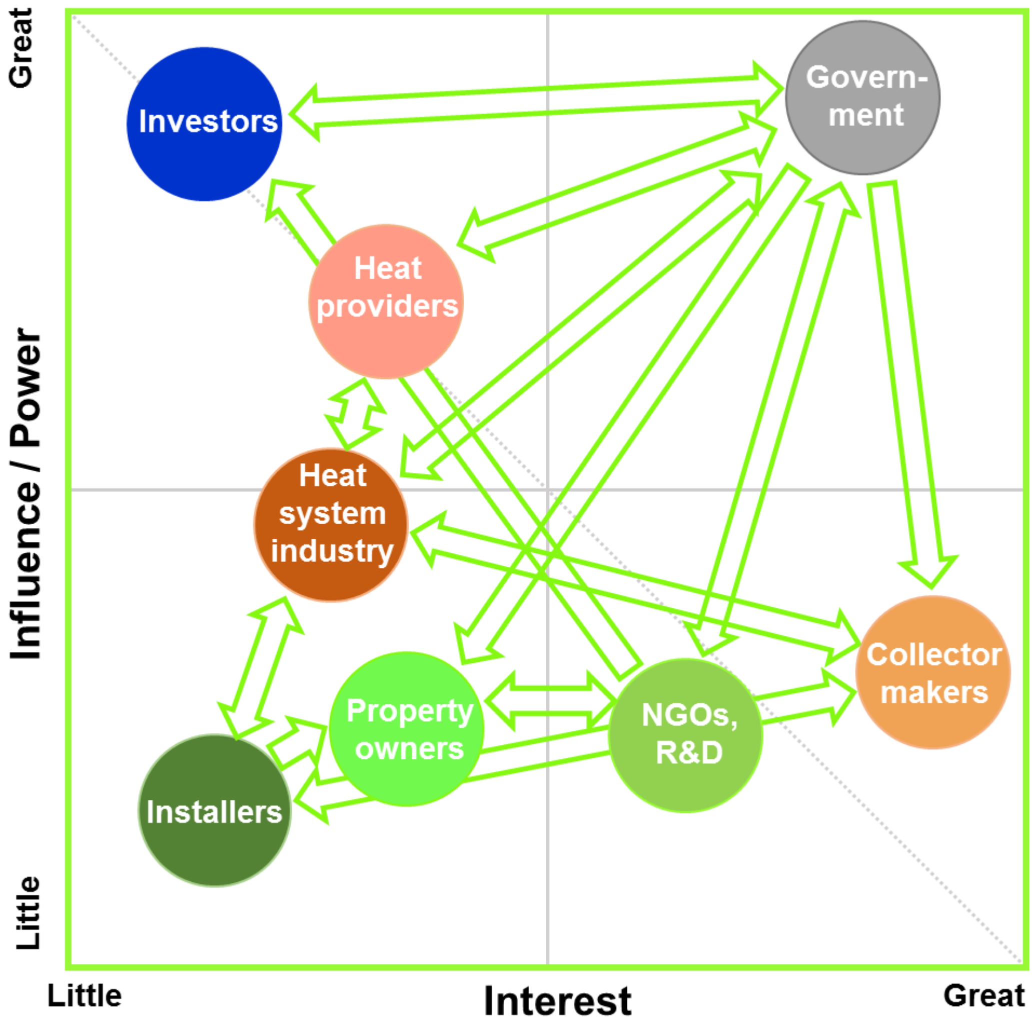

Fig. 1: Stakeholder matrix reflecting their influence and interest for small and medium size systems.

3.3. Fact-finding

To research the factual background of the articulations and the validity of the concerns expressed by stakeholders a comprehensive approach considering materials, environment, society, economics, legislation and energy issues was used.

In terms of sustainable development the overall question is, if solar collector systems can make a substantial contribution to carbon reduction targets in the next decades. Figure 3 summarizes the issues needing research.

(a) Materials. State of the art solar thermal collector systems are mainly based on metals like copper, aluminum or steel and silicate glass for the collector, piping and storage. As evident in many other fields of application, a transformation to mass technologies and full market penetration is often associated with a material substitution towards polymeric materials. Interestingly, also for solar thermal systems major research efforts are put on the development of all polymeric collectors, piping and storages. Here, two different approaches are discernible. On the one hand, high performance plastics and related processing technologies are developed for space heating systems. On the other hand, affordable, overheating protected solar thermal collector systems made from commodity polymeric materials are developed. Research work focuses on failsafe overheating protection measures and novel material formulations with improved long term performance in the temperature range between 80 and 95 °C. For both issues adequate solutions have been developed, so that the main issue is now the industrial implementation and transformation (Bradler et al., 2017; Fischer et al., 2016; Grabmann et al., 2016a, 2016b; Geretschläger and Wallner, 2016; Kahlen et al., 2010a, 2010b, 2010c, 2010d; Köhl et al., 2012; Kurzböck et al., 2012; Olivares et al., 2010a, 2010b; Povacz et al., 2014, 2016; Wallner et al., 2016). Therefore, investors and venture capital is needed to successfully implement polymer based alternatives, especially for often poor.

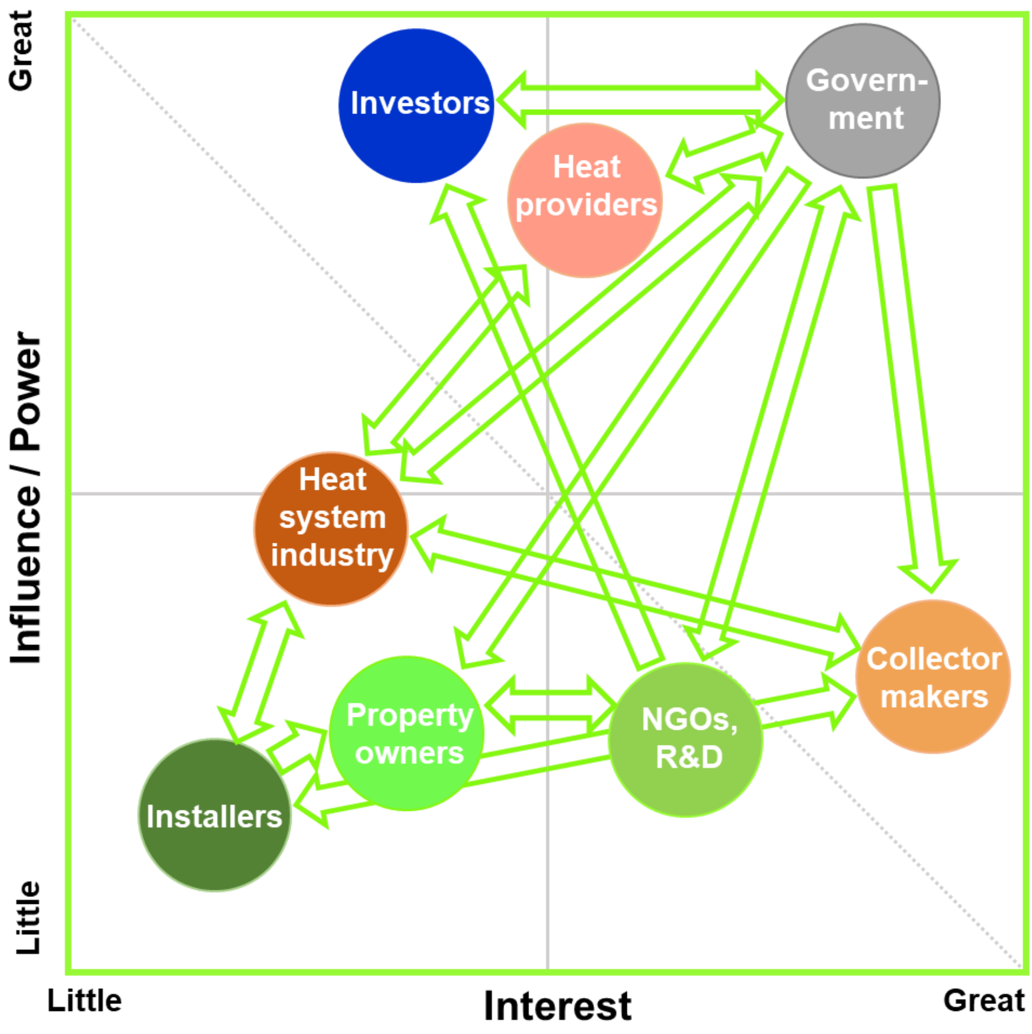

Fig. 2: Stakeholder matrix reflecting their influence and interest for large collector fields with seasonal storage by the example of district heat providers in Denmark.

(b) Energy. Weiss and Spörk-Dür (2018) have shown that the annual collector yield of all water-based solar thermal systems in operation by the end of 2017 worldwide was 388 TWh corresponding to a final energy savings equivalent of 41.7million tons of oil and 134.7 million tons of CO_2. 94% of the provided energy by solar thermal collector systems was used for domestic hot water heating. This is dominated by small-scale systems in single-family houses (63%) and larger applications (28%) for multi-family houses, schools, hotels etc. Swimming pool heating adds 6% and 2% of the energy supply and CO_2 reduction is contributed by solar combi systems for hot water preparation and heating. Regarding hot water preparation the most important issue is to replace electric hot water power systems in less-industrialized countries in sub-tropical and tropical climate zones. So far, no comprehensive investigation has been carried out to which extent this measure could contribute to fossil-based energy savings.

(c) The Environment. It is a well-known fact, that the use of metals, especially aluminum, for solar thermal collector systems has a significantly higher environmental impact than the use of polymeric materials (Arnaoutakis et al., 2017; Battisti and Corrado, 2005; Carlsson et al., 2014; Kicker, 2009; Kicker 2018; Koroneos and Nanaki, 2012; Singh et al., 2016; Weiss et al., 2015; Zambrana-Vasquez et al., 2015). In case of polymers a worse environmental effect was deduced for high performance polymers compared to commodity plastics such as polyolefins. Nevertheless, solar thermal systems reveal energetic and environmental amortization times ranging from 0.5 to 1.5 years depending on the system type and the location (Buchinger, 2017; Carlsson et al., 2014; Kicker, 2009; Weiß et al., 2015).

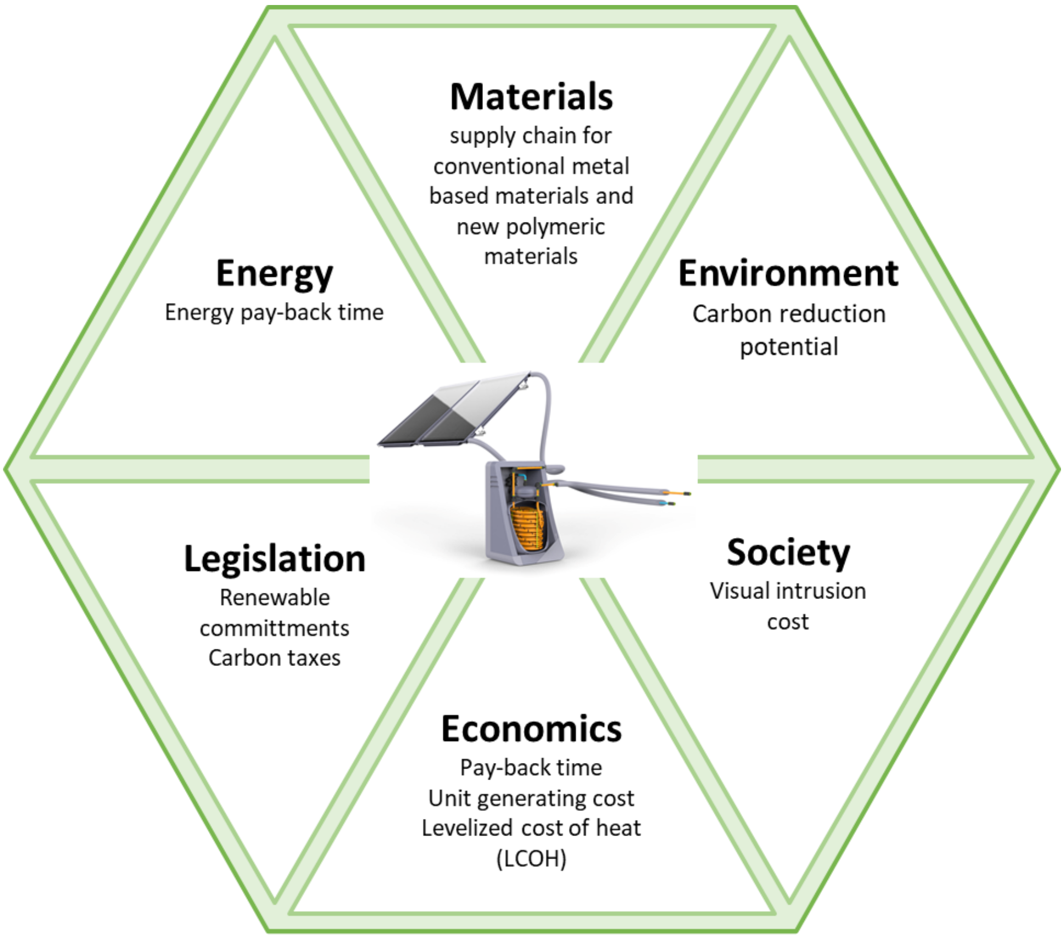

Fig. 3: Fact-finding summary.

(d) Legislation. The production of heat accounts for more than 50% of global final energy consumption. At present 75% of global energy use for heat (129 exajouls) is met with fossil fuels. About 1/3 of global energy-related carbon dioxide emissions (10 gigatonnes of CO_2) is related to the production of heat (Eisentraut and Brown, 2014). In 2015 many nations have agreed to hold global temperatures well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. This implies that global CO_2 emissions have to peak as soon as possible and that rapid emission reductions must follow (Streck, 2015). This agreement is a clear commitment to a sustainable development. However, this commitment still lacks a regulatory framework and is often not subject to public law. Moreover, current standardization procedures for solar thermal systems are dominated by individual countries and by the copper and glass industry.

(e) Economics. To assess the costs of the heat generated by solar thermal collector systems recently the levelized cost of heat (LCOH) evaluation procedure has been implemented. Important parameters affecting the LCOH are depicted in equation 1. Of significant importance are investment costs, the saved final energy and the lifetime (Fischer, 2017; Louvet et.al, 2017; Mauthner et al., 2016, Weiss and Spörk-Dür (2018).

$$LCOH = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{C_t(1-TR) - DEP_t * TR}{(1+r)^t} - \frac{RV}{(1+r)^T}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \qquad \text{(eq. 1)}$$

Where:

$LCOH$: levelized cost of heat in €/kWh
I_0: initial investment in €
S_0: subsidies and incentives in €
C_t: operation and maintenance costs (year t)
TR: corporate tax rate in %
DEP_t: asset depreciation (year t) in €
RV: residual value in €
E_t: saved final energy (year t) in kWh
r: discount rate in %
T: period of analysis in year

Fischer (2017) has shown that the LCOH for conventional, fossil oil based hot water preparation for a single family house (SFH) in Austria amounts to 10 €ct/kWh_{th}. The LCOH for conventional, metal based, pumped flat plate collector systems for a single family house are ranging from 12 to 15 €ct/kWh_{th}. It is a clear fact that the costs for solar hot water preparation with conventional flat plate collectors in SFH is too high and needs significant reduction. On the other hand, Buchinger (2017) shows that LCOH for an all polymeric pumped flat plate collector system can go down to 2 €ct/kWh_{th}, if the performance and the degree of utilization is high, which is especially achieved for small systems in hot climate regions. Weiss and Spörk-Dür (2018) have shown that analysis of Danish large-scale solar district heating (SDH) systems shows that economies of scale enable a huge potential for cost reduction: while the average LCOH for small domestic applications in Denmark ranges between 18.5 €ct/kWh for COMBI-single family houses and 12.1 €ct/kWh for domestic hot water for multi family houses, the average LCOH for large-scale systems (>10,000 m²) including the cost for a diurnal storage goes down to 3.6 €ct/kWh. For even larger systems (>50,000 m²) with seasonal storage attached a LOH of 4.9 €ct/kWh is achieved. The low LCOH in combination with a tax on natural gas makes large-scale solar thermal a commercial business case for district heating (con sumer) cooperatives all over Denmark.

(f) Society. The news-quotes show that present solar thermal collector systems are widely seen as large-scale installations for district heating. Although the market is dominated by systems for hot water preparation the stakeholders do not recognize this fact. Presumably, the situation is different for China.

For domestic hot water preparation in Europe solar thermal collector systems for single family houses are widely accepted by the public, but seen as much too expensive for an auxiliary source of heat for summer season. In this region solar thermal collectors are commonly replaced by photovoltaic modules and electric heaters. Interestingly, solar thermal hot water preparation for multi-family houses, which is already more economic than fossil based technologies or much more efficient than PV based systems, is of limited acceptance in society. Most likely, the outstanding advantages of this system type have not been communicated to the people, the building developers and the investors.

3.4. Synthesis of the facts

It is a clear fact that the costs for solar hot water preparation with conventional flat plate collectors in single family houses is too high and needs significant reduction. State of the art solar thermal collector systems are mainly based on metals like copper, aluminum or steel and silicate glass for the collector, piping and storage. As evident in many other fields of application, a transformation to mass technologies and full market penetration is often associated with a material substitution towards polymeric materials. It is a well-known fact, that the use of metals, especially aluminum, for solar thermal collector systems has a significantly higher environmental impact than the use of polymeric materials. While solar thermal heat systems based on novel all-polymeric materials find their way to hot water preparation for single family houses, they are still not considered for application in large collector fields or applications for industrial process heat generation.

3.5. Reflection and conclusions

While 2017about 94% of the energy provided by solar thermal systems was used for domestic hot water, currently a trend to larger solar thermal systems with seasonal storage coupled to district heating networks is discernible. Solar thermal at present contributes about 1% to total heat consumption. The share of solar district heating and solar process heat applications is steadily increasing despite it is still only representing 3 % of the global market (Weiss and Spörk-Dür, 2018).

The potential contribution is much larger. Many national governments seek to realize this potential by offering subsidies and feed-in-tariffs.

Assessing sustainable development for solar thermal heat systems is a complex discipline. The best heat system depends to a large extend on the climate region. If solar heat is intermittent, seasonal, economic storage of heat is advantageous. Significant cost reductions of solar thermal systems and a shift towards polymeric materials to regain market growth and to improve ecological performance is required.

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