REPORT

- Legionella and solar water heaters -

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Abstract

The literature study (chapter 2) gives an insight in the nature of the known outbreaks of legionnaires' disease and its causes. Currently it is not possible to show any statistically reliable results comparing the incidence of *Legionella* species in conventional hot water systems with solar assisted hot water systems.

Chapter 2 also offers valuable information on the behaviour of legionellae under the influence of temperatures that can be expected in solar assisted hot water systems.

In chapter 3 mathematical simulations are reported modelling the potential fluctuations in the population of legionellae in a solar heat storage tank being used for the (pre)heating of potable water. The modelling is limited to preheat systems and solar-only systems. By defining limits for low and medium risk applications on the acceptable concentration of legionellae in the water of the tank, an evaluation of the risk from *Legionella* is possible. The magnitude of the risk is determined by the number of hours per year such a limit is exceeded.

The results show how the legionella population fluctuates depending on the different application modes and the time of the year. It is obvious that legionellae can grow and die in a solar heat storage tank. The study tells us under which conditions the vulnerability to legionellae becomes high or remains low.

The design criteria showing the lowest vulnerability to legionella growth are: a low ratio of the storage tank volume to the collector area; and a tank with a small volume. As application criteria the collector should be optimally oriented and the system should be used regularly. The results for a low or medium risk application do not differ to such an extent that different criteria for both situations need to be formulated. This is also the case for the differences between preheat systems and solar-only systems.

The study will probably not be the last study on this subject. Proposals for further research are presented.

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Foreword

Although there is much known about legionellae in hot water installations, there is substantially less known about legionellae in the context of solar water heaters. From the known outbreaks of legionnaires' disease (1980 – 2010), 12% have been traced to hot water systems. Probably due to the relatively low proportion of hot water systems that incorporate solar heating, no cases are known that were definitely caused by solar water heaters.

The CEN-TC164 prepared a technical report entitled: "Recommendations for prevention of *Legionella* growth in installations inside buildings conveying water for human consumption", dated 2011-08-31 and referenced in this report as CEN/TR 16355. The CEN/TR 16355 focuses on conventional hot water systems and does not consider the applicability of its recommendations to solar water heaters.

The risk from *Legionella* in solar assisted hot water systems deserves special attention due to the dynamically changing temperature regime in the heat storage tank that includes both growth and disinfection temperatures. Moreover, a non-solar heat source is applied that may thermally disinfect the water from the solar thermal system.

The CEN-TC312 is preparing a report (Code of practice - Minimizing the risk from *Legionella* in solar assisted hot water systems -) that is building on the CEN/TR 16355. In preparation of this report, a study was executed to gain specific knowledge on the growth of legionellae in solar water heaters.

Commonly used terms defined

For this document, the following terms and definitions apply:

Hot water installation,

the complete installation, from cold water supply to draw-off points, and all components in-between.

- **Auxiliary heater**,

  a source of heat, other than solar, used to supplement the output provided by the solar energy system;

- **Solar water heater**,

  a generic term to designate a solar thermal system of type preheat system with auxiliary heater, solar solar-plus-supplementary system or solar-only system.

  - **Solar-only system**,

    a solar water heater without any auxiliary heat source.

  - **Solar assisted hot water system**,

    a generic term to designate a solar preheat system and its series-connected water heater, or a solar-plus-supplementary system. A solar assisted hot water system has a non-solar water heating part, named auxiliary part, and a solar heating part. There are various possible interactions between the two parts [1].

    - **Solar preheat system**,

      a solar hot water system to preheat water or air prior to its entry into any other type of water or air heater.

    - **Solar-plus-supplementary system**,

      a solar heating system that utilizes both solar and auxiliary energy sources in an integrated way and is able to provide a specified heating service independent of solar energy availability.

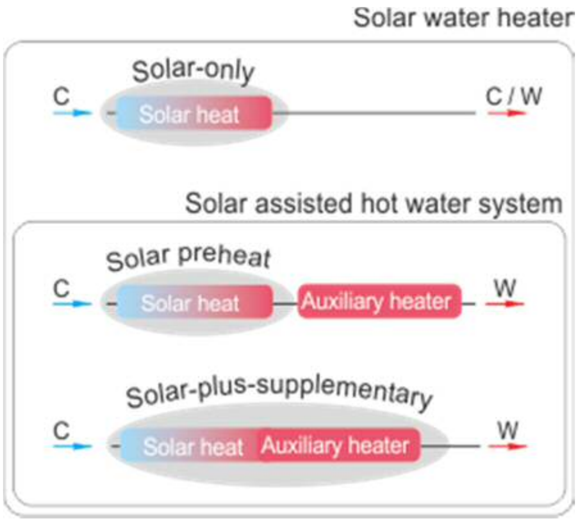

Figure 1 - Graphical representation of the different solar water heater types ('c': cold water, 'w': warm water).

Application,

the way that the solar water system is applied (e.g. collector orientation, heat demand, climatic region).

Decimal reduction time D,

the time taken to kill 90% of a population of bacteria or other organisms.

Legionella,

the name (epithet) of the genus of bacteria that encompasses over 50 species including over 20 that have been associated with infection in man. (Legionella is analogous to Homo the genus to which humans belong).

Doubling time

the time taken for the population to double in number, also called the generation time

Generation time

see doubling time

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[1] Prevention of *Legionella* growth requires measures to be applied to all devices whose function is to heat up the potable water.

legionella,
a bacterium of the genus Legionella (analogous to a hominoid).
legionellae, *the plural of legionella (analogous to hominoids)*
L. pneumophila,
the name of a species for which pneumophila is the species specific epithet (analogous to sapiens *in* Homo sapiens*). The most common cause of legionnaires' disease.*

1 Introduction

1.1 The report

The report describes the outcome of a study to gain more knowledge of the behaviour of legionellae in solar water heaters and comprises a literature study and computer assisted mathematical simulations. The results are used to substantiate the CEN-TC312 report (Code of practice - Minimizing the risk from legionellae in solar assisted hot water systems -).

1.2 Legionella and solar thermal hot water systems

The solar part of a solar water heater is, in broad outline, located between the cold water supply and the non-solar water heater. Several installation designs, combining the functions of the solar part of the system and the non-solar water heater, are currently applied.

Legionellae can originate from all parts of the hot water installation: from the cold water supply (cold feed) to the hot water outlets and all installation components in between. When considering the risk from *Legionella*, the installation as a whole needs to be evaluated.

The CEN/TR 16355 gives valuable information on how to minimize the risk from *Legionella* in a hot water installation. However, CEN/TR 16355 does not consider the application of a solar water heater.

Since 2000, there have been expressions of concern about the potential for solar water heaters (SWHs) to encourage growth of *Legionella* species, the cause of legionnaires' disease, to a greater degree than conventional hot water systems. The primary reason for this is the perception that SWHs are more likely to contain a significant volume of water at a temperature conducive to the growth of legionellae. That is at temperatures between 20 and 50 °C and in particular between 32 and 42 °C. However, the reality is more complex.

In the context of legionella control the factors that need special consideration for solar water heaters are:

- the use of storage tanks with frequently changing water temperatures in the range of 10 °C to 80 °C, so that part of the tank and water is within the temperature range favourable to the growth of *Legionella* species;
- the use of a storage tank that frequently and for long periods is at a temperature level above 65 °C and, as such, disinfects the legionellae and biofilms within the tank;
- the use of non-solar heat sources that may thermally disinfect the hot water.

The temperature regime in the heat storage tank is fluctuating on a daily base. Under the influence of weather conditions, the daily temperature cycle can differ from day to day and is influenced by the time of the year and the pattern of hot water withdrawal. This fluctuating temperature regime in the tank will cause a complex process of growth and death of *Legionella* species.

A special case is the solar-only systems, that are applied without a non-solar water heater. Those applications cannot always guarantee a high enough hot water temperature at the draw-off points as required by EN 806-2 (60 °C) and many national regulations within Europe. As such, solar-only systems are not always allowed within Europe and are not relevant in the context of the CEN/TR 16355 report.

2 Literature study

2.1 Review of reports of health risks from solar hot water systems

Since 2000, there have been expressions of concern about the potential for solar water heaters (=SWH) to encourage growth of *Legionella* species, the cause of legionnaires' disease, to a greater degree than conventional hot water systems. The primary reason for this is the perception that SWHs are more likely to contain a significant volume of water at a temperature conducive to the growth of legionellae. That is at temperatures between 20 and 50 °C and in particular between 32 and 42 °C.

The assessment of the risk of, or potential for, any equipment or system using water being a source of legionnaires' disease requires consideration of five points (Anon 2010):

a) *Contamination.* An evaluation of the likelihood of the equipment becoming contaminated by legionellae, including assessment of the cleanliness, temperature and integrity of the water supply.

b) *Amplification.* Consideration of the likelihood that any legionellae entering the system will proliferate, including an assessment of conditions such as the temperature, water change rate, areas of static or slow water movement, availability of nutrients from its construction materials and how conducive the conditions in general are to microbial growth.

c) *Transmission.* An assessment of whether droplets or aerosols are likely to form and spread.

d) *Exposure.* Determination of the risk that droplets or aerosols will be inhaled or contaminated water aspirated (pass into the lungs accidentally during swallowing of contaminated water).

e) *Host susceptibility*. An evaluation of the nature of the exposed population, taking account of their vulnerability when exposed to legionellae.

Legionnaires' disease was first recognised in 1976. Since then knowledge of the factors controlling the potential risk from recognised sources of legionnaires' disease, such as hot and cold water systems, has been derived from evidence obtained from the epidemiological and microbiological investigation of outbreaks of legionnaires' disease. In addition, once systems were identified as sources of legionnaires' disease, surveys including microbiological monitoring were carried out to establish the factors contributing to the colonisation of such systems. Outbreaks of infection inevitably occur mostly where large numbers of people are exposed such as hotels and hospitals. In such large buildings conventional hot and cold water systems are much more common than SWHs so that an appreciable body of information has been gathered on conventional systems but not hot water systems incorporating heating by solar collectors.

The lack of epidemiological reports linking outbreaks of legionnaires' disease to SWHs and the lack of microbiological evidence of the contamination of SWHs has been cited as evidence that they are safe. However, legionnaires' disease is relatively rare and lack of epidemiological evidence linking the disease to SWH probably reflects the relative scarcity of SWH in comparison to conventional systems. In the preparation of this report, we have carried out extensive surveys of published peer-reviewed literature. In addition other evidence was sought by review of searches carried out using a variety of search engines and requests for information from members of the UK Water Management Society (a learned society of about 1000 members encompassing experts in all aspects of water safety and treatment).

The following databases were utilised: Google http://scholar.google.co.uk/Scholar; Information Bridge, US Department of Energy Scientific and Technical Information http://www.osti.gov/bridge; Medline Plus http://www.nlm.nih.gov/medlineplus/; PubMed http://www.ncbi.nlm.nih.gov/pubmed/; Scientific Commons http://en.scientificcommons.org/; Scirius http://www.scirus.com/; USA.gov for Science http://www.science.gov/index.html; WHO

Injury Prevention Literature Update and Archive database http://www.safetylit.org/; WorldWide Science http://worldwidescience.org/.

2.1.1 Outbreaks of legionnaires' disease associated with hot water systems incorporating solar heating

An outbreak olegionnaires' disease occurred in a Brazilian hospital. Legionellae were isolated from the showers in the renal transplant unit that was fed from a solar heated hot water system. In the initial investigation the type of *Legionella* that was responsible for the patients' infections was only isolated from the condensate of a chiller battery in the air-conditioning system (Levin *et al.* 1991). This suggests the infection may have been of external origin. Following the outbreak, in an attempt to control the colonisation, the hot water system was periodically super chlorinated and flushed. Despite this, cases continued to occur and legionellae including *L. pneumophila* serogroup 1, the cause of the cases, continued to be detected in the hot water system. Colonisation and cases ceased to occur when the hot water system was replaced with cold water fed instantaneous electric showers (Levin *et al.* 1995). These observations clearly indicate that the hospital hot water system was the cause of the infections. However, the reports provide insufficient information on the system design and colonisation to determine if the solar component of the system was a critical or even contributory factor to the system becoming colonised with legionellae and causing the outbreak.

The outbreak in Brazil is the only report we have been able to find in peer-reviewed publications, to date, implicating a hot water system that incorporated solar heating as the cause of an outbreak. There are two other instances known to the authors that have never been published in peer-reviewed articles.

In September to October 1996 three cases of Legionnaires' disease occurred in a hotel in Antigua. The town water supply to the hotel, and the hot and cold water distribution systems were contaminated with *Legionella pneumophila*. Highest concentrations were detected in the hot water system, particularly the hot water storage tanks and at taps in rooms that had not been used for several days. The hot water storage tanks were of the solar-plus-supplementary type with a solar storage tank filled with potable water and incorporating an auxiliary storage water heater. It was concluded that the hotel's hot water supply was the source of the outbreak (Hospedales *et al.* 1997 (abstract only) and JV Lee unpublished data). However, the solar heating system was in the process of being installed and it was concluded that the outbreak was the consequence of the disruption to the hot water system rather than the presence of the solar system itself.

In 1996, a small cluster of cases of legionnaires' disease was associated with a hotel in Marmaris, Turkey (J V Lee unpublished results). The hotel hot water system was implicated. During the cooler months of the year the water was heated by means of an oil fired boiler and during the summer by solar collectors. The cases occurred in the early part of the year and the solar tanks and associated pipes were implicated as the source of the infections because they had been left connected to the hot water system during the cool months and had been at temperatures conducive to the growth of legionellae (J V Lee unpublished data).

These three examples of outbreaks indicate that hot water systems incorporating solar heating can be the source of legionnaires' disease in much the same manner as hot water systems heated by other 'conventional' means.

2.1.2 Incidence of Legionella in solar water heaters

There is very little information on the incidence of *Legionella* species in SWHs. In preparation for the Olympics in Athens, Greece, 385 hotels were investigated for the presence of legionellae in their hot water systems (Mouchtouri *et al.* 2007b). Legionellae were not isolated when the sample temperature was greater than 60.3 °C. The majority of the systems were heated by oil but a small proportion were heated by electricity or by solar collectors. Approximately 10% of the SWHs examined were colonised with legionellae in contrast to 69% of the systems heated by oil. It was concluded that storage water heating powered directly by electricity or solar water heaters were less likely to be colonised than those heated by oil. However, the same workers found that thermal disinfection was more effective in hot water systems heated by oil than in the SWHs (Mouchtouri *et al.* 2007a).

In Germany a survey of hot water systems in single-family residences showed that legionellae could not be detected in hot water systems heated by instantaneous water heaters whereas 12% of houses with hot water storage tanks contain legionellae with counts of up to 100,000 cfu/100 ml (cfu, colony forming units) (Mathys *et al.* 2008). Legionellae were only detected in two (4.2%) of the 48 SWHs examined in contrast to 13% of 352 other systems. Solar water heaters did not seem to promote the proliferation of legionellae but it should be noted that the authors did not report what time of year the survey was undertaken. This is an unfortunate omission as the time of year might have influenced the results for SWHs. The authors concluded that the temperature of the hot water was the most important determining factor for the multiplication of legionellae. Hot water systems with temperatures below 46 °C were most frequently colonised.

In Denmark two studies were carried out on domestic water heaters. In the first, the growth of bacteria was compared in 12 'solar prepared' tanks and 12 traditional tanks. The work was undertaken in preparation for the new Danish building regulations which it was thought might make 'solar prepared' tanks mandatory. They found no significant difference in the bacterial counts which were low in comparison to other investigations on larger systems in flats. In the second follow up study hot water samples were taken from actual domestic hot water systems and checked for legionellae. Five out of 24 water hot water tanks contained legionellae. None were detected in the solar prepared tanks (solar heating tank with no solar collector connected yet), but one of the traditional hot water tanks and 4 out of the 8 solar tanks contained legionellae (Bagh and Ellehauge 2001). The solar prepared tanks that were not actually connected to solar collectors were included to see if the larger volume increased the risk of colonisation. However, since the solar collectors were not connected it is unlikely that these tanks reached temperatures that might be conducive to growth so it is not surprising that legionellae were not detected in them. In contrast the solar tanks that were connected to collectors would have reached temperatures conducive to growth and indeed legionellae were detected in these tanks.

2.1.3 Conclusion on outbreaks related to solar assisted hot water systems

There are very few studies published comparing the incidence of legionellae in conventional hot water systems in comparison to SWHs. The number of SWHs studied to date is too small to provide statistically reliable results. More data will be required to determine whether there is, in reality, any greater risk of SWHs becoming colonised with legionellae than other types of hot water system. Such studies would need to be carefully designed and controlled to enable the comparison of SWHs with conventional systems of otherwise similar age and construction. However, in the absence of such studies, it is clear that legionellae can occur in SWHs just as they can in other hot water systems and that legionellae can sometimes multiply in SWHs that can then become the source of legionnaires' disease. Thus SWHs, like all water systems should be designed to minimise the risk of legionellae growing within them.

2.2 Effect of temperature on the survival of legionellae

It is widely recognised that *L. pneumophila,* the most common cause of legionnaires' disease, grows in water at temperatures between 25 °C and 45 °C with an optimal temperature in the range of 32 to 42 °C (Surman-Lee *et al.* 2007). Using a temperature gradient apparatus Konishi *et al.* 2006 found that *L. pneumophila* could not grow beyond 44.2 °C. Thus below

25 °C *L. pneumophila* grows slowly, if at all, but can survive for prolonged periods or even indefinitely whereas above 45 °C it begins to die. The effect of disinfectants is usually expressed as the decimal reduction time D which is the time taken to kill 90% of a population. Dennis *et al.* 1984 in England and Schulze-Robbecke *et al.* 1987 independently in Germany, studied the effect of temperature on *L. pneumophila* and achieved very similar results. At 50 °C the decimal reduction time was 111 min and at 60 °C about 2 min. These results would suggest that at 70 °C D would be only a few seconds.

2.2.1 The rate of death at temperatures above 50 °C

Stout *et al.* 1986 carried out a more extensive investigation of 75 isolates representing 10 *Legionella* species. At 60 °C the decimal reduction time ranged from 1.3 to 10.6 min. They found that for *L. pneumophila* at 60 °C, D was about 3 min (range 2.3 to 5.0) for most strains. The most resistant species was *L. micdadei* with a range of 4.5 to 10.6. At 70 °C D ranged from 0.7 to 2.6 min while at 80 °C the range was 0.3 to 0.7 min. Extrapolation of these results backwards would suggest that the decimal reduction time at 50 °C for *L. pneumophila* would be about 9 minutes. This appears to be far too short as, in the routine isolation of legionellae from water, samples are heated at 50 °C for 30 min to suppress the background flora while permitting good recovery of *L. pneumophila* and other pathogenic *Legionella* species. The higher decimal reduction time at 50 °C determined by other workers (Dennis *et al.* 1984; Schulze-Robbecke *et al.* 1987) appears to be a more likely estimate of the true value. All three groups of workers use very different methods and this may explain the differences found. The combined data from all the studies indicate that the decimal reduction time at 60 °C is about 2 to 3 min for most strains of *L. pneumophila*.

In the absence of appropriate control measures, it is common to detect *L. pneumophila* in the cool bottom of stratified hot water storage tanks at levels of up to 100,000 cfu per litre (J. V. Lee unpublished results; Makin 2009; Mathys *et al.* 2008). *Legionella pneumophila,* in conjunction with natural supporting microflora, can be grown in model systems fed only with tap water and no additional nutrients other than those available from plumbing materials incorporated into the models. The conditions in these models systems simulate those in artificial water systems and under these conditions legionellae can grow in biofilms on surfaces of materials at concentrations of about 10,000 to 200,000 cfu per square centimetre and in the aqueous phase up to 10^6 cfu/litre depending upon the nature of the material and temperature (Rogers *et al.* 1994a; Rogers *et al.* 1994b). The highest numbers were achieved at 40 °C, lower numbers were detectable at 50 °C and none was detectable at 60 °C (Rogers *et al.* 1994b).

Legionellae have been shown to grow within the variety of protozoa both in natural and artificial water systems. Protozoa produce cysts which are a means of them surviving periods when environmental conditions are not suitable for their growth. The cysts are generally believed to be more resistant to physical and chemical agents than the vegetative protozoa and legionellae. However, legionellae can become incorporated within protozoal cysts and therefore be protected by them. Although protozoal cysts are generally considered to be relatively heat resistant there is little hard information available. *Acanthamoeba polyphaga* is an amoeba that occurs in household water systems, causes eye infections in humans and in which *L. pneumophila* can grow. Cysts of an *A. polyphaga* have been shown to survive for at least 60 minutes at 60 °C although they died slowly at 65 °C with the decimal reduction time of about 2.5 min. Thus theoretically, incorporation within cysts of *A. polyphaga* at least might enable *L. pneumophila* to survive heating at 60 °C for one hour. On the other hand heating to 60 °C has been shown to be effective at not only killing legionellae in the aqueous phase but also those growing in combination with supporting microflora including protozoa on surfaces in biofilms (Rogers *et al.* 1994b; Saby *et al.* 2005).

2.2.2 The rate of growth of legionellae in hot and cold water systems

To estimate the time necessary for a hot water system to become colonised following contamination with legionellae, or to become recolonised after disinfection, it is important to know how quickly legionellae can grow under the optimal temperatures for growth in water. There are surprisingly few estimates of the rate of growth of legionellae under natural conditions. In human monocytes doubling times of as little as two hours have been recorded (Horwitz and Silverstein 1980). However, this observation is unique and other authors have recorded much slower growth rates. In a human cell line U937, similar to the macrophages that are infected during legionnaires' disease, at 37 °C the generation time was found to be 6 hours (Pearlman *et al.* 1988). The doubling time in *A. castellani* at 35 °C ranged from 7 to 28 hours depending upon the *Legionella* species and for most species it was about 10 hours. In continuous culture simulating natural growth conditions, dilution rates equivalent to generation times of 8 to 14 hours at 30 °C to 40 °C were used (Mauchline *et al.* 1994; Rogers *et al.* 1994a; Rogers *et al.* 1994b). Thus, it appears likely that in nature the generation time probably ranges from between 6 and 14 hours at 37 to 40 °C.

2.2.3 Disinfection of hot water tanks

As noted above the cool base of stratified hot water tanks can harbour significant numbers of legionellae. This has been recognised for many years. A common strategy to control this in large hot water storage tanks in commercial buildings and hospitals is to ensure that the whole tank is heated to 60 °C for at least an hour once-a-day (HSE 2000). This is commonly achieved by installing a small anti-stratification pump to circulate water from the top of the tank to the bottom at periods of low use such as during the night. It has been suggested that a similar strategy be extended to SWHs by ensuring that they are heated to at least 60 °C daily using supplementary heating as necessary. However, for this to be most efficient in solar heated tanks the supplementary heating, if needed, should NOT be undertaken at night as this could lead to insufficient cold water being present in the tanks in the morning for the solar collectors to work. With solar heated tanks the best time for supplementary heating to be applied, if it is needed, would be when the power of incident solar radiation is decreasing while the solar heated tank has reached its highest temperature of the day. This would normally be at least 4 hours after solar noon. The disadvantage of this approach is a requirement to use non-solar energy sources on days when the solar input is insufficient to raise the temperature to at least 60 °C. It is clear that, as with conventional hot water storage tanks, there is some risk of legionellae growing in solar hot water tanks when the temperature does not reach temperatures that will kill legionellae.

2.2.4 Colonisation of hot water systems by legionellae

The risk of a hot water system being the source of legionnaires' disease depends on a number of factors. The hot water storage tank is often the first point of amplification of legionellae in a hot water system. The organisms growing within the tank may subsequently be transported elsewhere within the system to colonise other parts particularly in the region of the draw-off points. It is colonisation of the draw-off points that is usually responsible for infection. Prevention is multifactorial and minimisation of growth within the hot water storage tanks is only one factor. The greater the complexity of a hot water system the greater the risk of it becoming colonised at one or more points. Thus, hot water systems in hotels and hospitals are at greatest risk of becoming colonised and causing infection. The risk of a single household hot water system becoming colonised is generally less because there are fewer points to become colonised and water turnover is often relatively high. In contrast multi-occupancy buildings such as a block of apartments with a shared hot water system are at a high risk of becoming colonised (Lück *et al.* 1993). With high risk systems in buildings housing high risk populations, such as hospitals, there is clearly a need to ensure the hot water storage tanks do not become colonised and daily heating of the tank to 60 °C or above is a reasonable precaution. However, whether this is necessary for relatively low risk application such as single household systems (see table 4) to reliably minimise the risk of legionellae growing is questionable.

2.2.5 Heat disinfection and recolonisation of a 250 L solar hot water tank

Let us consider a worst case scenario for a 250 L solar hot water tank incorporating a dedicated 105 L solar volume and a total internal surface area of the tanks plus coils of 42,000 cm^2. Assume the tank has been between 35 and 45 ºC for some weeks and the population of *L. pneumophila* in the water has reached 10^6 cfu/L and in the biofilm on the surfaces is 2×10^5 / cm^2.

The total *L. pneumophila* population = Population in water + population on surfaces

Therefore total population = $(250 \times 10^6) + (42{,}000 \times 2 \times 10^5) = 2.5 \times 10^8 + 8.4 \times 10^9 = 8.65 \times 10^9$

Note that about 98% of the *L. pneumophila* population is on the surfaces which is a typical value determined in model systems and infected plumbing test rigs (Rogers *et al.* 1994a; Saby *et al.* 2005).

Assuming that at 60 ºC the decimal reduction time D for *L. pneumophila* is 2.5 – 5.0 minutes (Stout *et al.* 1986) heating the tank to 60 ºC for one hour will achieve at least 12 log reductions so that the legionella population should effectively be eliminated from throughout the tank.

If the tank became reinoculated immediately with a single *L. pneumophila* and the supporting flora how long would it take to reach a population in the water that is considered not acceptable in national guidelines? In the UK, the national HSE guidelines suggest that legionellae should ideally remain below 10^2 cfu/L, i.e. undetectable by the most commonly used methods of culture. If the count reaches 10^3 cfu/L, disinfection is generally recommended. If we assume that 98% of the legionella population is on the surfaces then 10^2 cfu/L would be equivalent to a total population of 5×10^5 in the whole tank. Assuming a generation time of 6 – 14 hours under optimal conditions it would take 19 generations (2^{19} = 524,288) or 114 – 266 hours or 4.75 – 11 days to reach such a population. This calculation assumes worst-case conditions of optimum temperature throughout the tank and no water usage. However, if the tank were initially inoculated with a larger number of legionellae it would take proportionally less time to recolonise the tank to the same level. None the less, these calculations suggest that daily heating of the solar hot water tank to 60 °C in practice is probably excessive to achieve reasonable levels of control in solar hot water tanks. In practice the tank being heated to at least 60 °C for at least one hour once a week should achieve adequate control for the single household situation. It is suggested that such a regime should be investigated by incorporating solar hot water tanks in test rigs similar to those utilised by (Loret *et al.* 2005) to study disinfection methods for hot water systems.

2.2.6 The use of methods other than heat to control legionellae

A wide variety of methods have been used as alternatives to heat for the disinfection of water systems and for long term control of the growth of legionellae where water temperatures are in the regions supporting the growth. Chlorine and chlorine dioxide have been used extensively for both disinfection by single (shot) dosing or long-term control by continuous dosing at lower levels. Copper silver ionisation can also be used for long-term control but the levels of silver (20 to 40 µg/L) required to achieve control (HSE 2000) are in excess of those permitted for drinking water in some countries such as France (Loret *et al.* 2005). Since February 2013 it has become illegal to use copper as a biocide in potable water systems as appropriate approval under the Biocides Directive has not been sought within the necessary timescale. Derogation has been applied for by the UK but the outcome of this application will not be known for some months. Periodic chemical disinfection does not appear to be as efficient at controlling biofilm as thermal disinfection at 70 °C or maintaining hot water temperatures throughout the system at greater than 55 °C (Saby *et al.* 2005). Chemical disinfectants may have long-term adverse effects on pipe materials and may also produce disinfectant by-products that are considered potentially carcinogenic. The use of chemical disinfectants therefore requires a degree of careful control and management that is probably not suitable for application in single households.

3 Mathematical Simulations

3.1 Introduction

In the context of Legionella control the factors that need special consideration for solar water heaters are:

- the use of storage tanks with frequently changing water temperatures in the range of 5 °C to 80 °C;
  The tank is within the temperature range favourable to the growth of legionellae.
- the use of a storage tank that frequently and for long periods is at a temperature level above 65 °C;

  The tank can also be at a temperature range suitable for the disinfection of legionellae and biofilms.

The temperature regime in the heat storage tank is fluctuating on a daily base. Under the influence of weather conditions, the daily temperature cycle can differ from day to day and is influenced by the time of the year and the pattern of hot water withdrawal.

The fluctuating temperature regime in the tank will cause a complex process of growth and death of legionellae. In order to evaluate the risk from legionellae, the temperature regime and its effect on the legionella concentration needs to be evaluated taking into account all the dynamic effects occurring in the solar heat storage tank and during a long enough period to 'see' all the possible conditions in succession.

3.1.1 Symbols

$\mathbf{A_{col}}$	Collector aperture area in m^2;
η_o	the zero-loss collector efficiency;
$\mathbf{a_1}$	the first order heat loss coefficient of solar collector in W/(m2K);
$\mathbf{a_2}$	the second order heat loss coefficients of solar collector in $W/(m^2K^2)$;
$\mathbf{V_{store}}$	the volume of the solar heat storage tank in l;
V/A	V_{store} / A_{col}
$\mathbf{U_{sto}}$	the heat losses of the storage tank in W/K;
$\mathbf{H_{col}}$	the annual solar irradiation in the collector plane in MJ/(m^2 a);
$\mathbf{T_{amb}}$	the ambient (outside, annual average) temperature in °C;
$\mathbf{T_{cold}}$	the cold water temperature in °C;
$\mathbf{T_{demand}}$	the temperature of the water at the point of use in °C;
Cfu	the colony-forming unit of Legionella;
DO	Doubling time of a Legionella concentration in hours;

3.1.2 Scope of the simulation model study

The study is limited to:

- the solar preheat and the solar-only system designs;
- a tank containing potable water, assuming a heat exchanger to transfer the heat from the collector to the potable water;
- the solar water heater as part of a hot water installation.

3.1.3 Limitations

The following limitations of the study need to be taken into account interpreting the results and conclusions of the study.

- Solar thermal systems for any other type of application, like space heating or space heating and water heating, are not subject of this study.
- Heat storage tanks with a combined function for solar heat storage and auxiliary heat storage are excluded from the study.

- Only low risk and medium risk applications of the solar water heater are subject to this study (see table 4). High risk applications need a high level of management of the hot water system that goes beyond the scope of this study.
- Because of the complexity of the matter, it is unavoidable that many assumptions need to be made. These are assumptions on the design and dimensions of the solar water heater, the behaviour of the *Legionella* population and the type of demand for hot water layout upon the system. The assumptions are listed in 3.2.

  For this reason and the fact that still many things are unknown on the fluctuations in the population of legionellae in a hot water storage, the study should be seen as a sensitivity study, showing critical processes, trends and the order of magnitude of the potential fluctuations in the population of legionellae.
- The solar water heater is one of the components of a hot water installation. As such there are more potential risks from legionellae caused by other parts or components of the hot water system. For a safe use of hot water the total system needs to be looked upon.

3.2 Method

The potential fluctuations in the population of the Legionella in a solar heat storage tank is investigated by means of mathematical simulation [2].For typical solar water heater designs and applications and climatic regions within Europe the fluctuations in the population of legionellae is quantified and the consequent risk evaluated.

Since the highest legionella levels are to be found at the end of a calendar year, the calculations span over two years. For this purpose one climatic data file is used twice in succession.

Assumptions on the design and dimensions of the solar water heater and the behaviour of the legionellae are made and illustrated in the following paragraphs.

3.2.1 Solar domestic hot water system

For the calculations of the behaviour of the solar water heater, the following assumptions are used.

Table 1 Assumptions on the design and application of the solar hot water system

Parameter:	Value							
A_{col} =	V_{store} / 25, V_{store} / 40, V_{store} / 55							m^2
η_o =	0.8							-
a_1 =	3.5							$W/(m^2.K)$
a_2 =	0							$W/(m^2.K^2)$
Collector azimuth:	South, South-West							
Collector tilt angle:	Latitude of the geographical location, almost horizontal (20^o), vertical (90^o)							^{o}
V_{store}	150							litre
U_{sto}:	1.5 W/K (label class ‘C’ according to Ecodesign energy label for heat storages)							
Climatic regions:	De Bilt (NL)	Eskdalemuir (UK)	Evora (PT)	Stockholm (SE)	Ukkel (BE)	Valencia (ES)	Wurzburg (DE)	
H_{col} =	4 022	3 491	6 654	4 318	3.851	6.751	4 567	$MJ/(m^2 a$ *))
T_{amb} =	9.5	7.1	15.8	6.7	10.1	16.9	9.4	^oC
T_{cold} =	10	5	15	5	10	15	10	^oC
Latitude =	52.11	55.27	38.57	59.33	50.80	39.47	49.79	^{o}
Longitude =	5.18	-3.25	7.91	18.06	4.33	-0.38	9.95	^{o}
T_{demand}	Pre-heat system: 60			Solar-only system: 40				^oC
	The tank is filled with potable water							
Daily hot		Pre-heat system:		Solar-only system:				l/day

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[2] ZBOIL48, version 1.06, TNO

water consumption	'Over dimensioned': 'Average': 'Under dimensioned':	50% of V_{sto} 100% of V_{sto} 200% of V_{sto}	50% of V_{sto} x $(60-T_{cold})/(T_{demand}-T_{cold})$ 100% of V_{sto} x $(60-T_{cold})/(T_{demand}-T_{cold})$ 200% of V_{sto} x $(60-T_{cold})/(T_{demand}-T_{cold})$	
Daily heat load **):	Over dimensioned: 50% of V_{sto} Average: 100% of V_{sto} Under dimensioned: 200% of V_{sto}			l/day
Daily load profile:	07:00h 20% of daily hot water consumption 08:00h 20% of daily heat load 13:00h 20% of daily heat load 18:00h 20% of daily heat load 19:00h 20% of daily heat load			
Weekly load profile:	Daily: 7 days a week Working days: Mon, Tue, Wed, Thu, Fri Weekends: Sat, Sun			
Calculations	1 h time step. For each climate two equal years in succession are used.			

*) on collector plane

**) the terms 'over dimensioned and under dimensioned refer to the sizing of the heat storage tank

Table 2 - terms explained

Collector azimuth is the horizontal viewing angle of the collector in °.0° is facing south;
Collector tilt angle is the angle between the horizontal plane and the plane of the collector surface in °. 0° is horizontal, 90° is vertical;
Daily heat load is the hot water withdrawal during one day in l;
Daily load profile is the distribution of the daily heat load over the day in %;
Weekly load profile is the days of a week with hot water withdrawal;

The reference (default) system is defined as a system with a collector facing south, with a tilt angle equal to the latitude, an 'average' daily heat load and a 'daily' weekly load profile.

3.2.2 Fluctuations in the legionella population

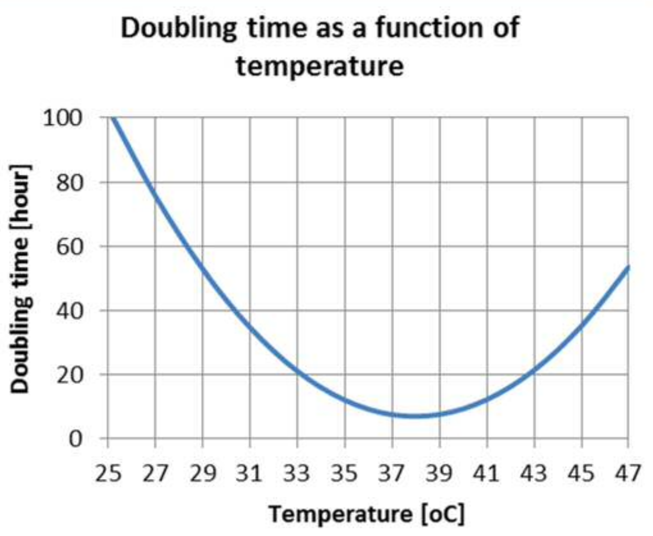
For the determination of the legionella concentration in the heat storage tank the following assumptions are made.

1. 98% of the legionellae in the tank is located on the inner wall. 2% of the Legionella is located in the water of the tank [3].
2. The Legionella concentration on the inner wall is subject to growth or dying under the influence of the water temperature in the tank.
   The model calculations use 11 distinctive vertical layers of water in the tank. However, the average temperature is used to calculate the fluctuations in the legionella concentration (= cfu).
3. The complete inner wall surface is assumed to be populated with legionellae with a minimum concentration of 100 cfu/m^2.
4. The concentration of legionellae in the water, being 2% of the concentration on the inner wall, is decisive for the risk of legionnaires' disease.
5. In a low risk application of the solar water heater, a maximum cfu/l of 5 x 10^5 is allowed.
6. In a medium risk application of the solar water heater, a maximum cfu/l of 5 x 10^3 is allowed.

For the fluctuations in the legionella population on the inside surface of the tank the following rules apply:

[3] Rogers et al, 1994a; Saby et al. 2005).

Table 3 Assumptions made for modelling the fluctuations in the population of legionellae under the influence of the temperature regime in the tank.

<table>
<tr><td>T_{store} =</td><td>Evolution:</td><td>Remarks:</td></tr>
<tr><td>< 25 °C</td><td>No growth</td><td>Stable population</td></tr>
<tr><td>≥ 25 °C and < 47 °C</td><td>Growth</td><td>

Calculation per hour:
– $DO = 0.5702 \times T_{store}^{\wedge 2} - 43.3 \times T_{store} + 829$
– $Cfu_{i+1} = Cfu_i + (0.8677 \times DO^{\wedge -1.08}) \times Cfu_i$
Evaluation of risk level:
– $Cfu \times 0.02 / V_{store}$ /l</td></tr>
<tr><td>≥ 47 °C and < 55 °C</td><td>No growth</td><td>Stable population</td></tr>
<tr><td>≥ 55 °C</td><td>Disinfection</td><td>Calculation per hour:
– $Cfu_{i+1} = Cfu_i - 0.999 \times Cfu_i$</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

3.2.3 Evaluation of the risk from *Legionella*

The risk from legionellae in the solar water heater is evaluated based on the concentration of legionellae in the water of the tank being 2% of the concentration on the inner wall.

The criteria used for this evaluation depend on the type of application according to Table 4.

Table 4 Building categories and risk levels based on SIA 385/1 (CH)

Risk Level	*Building Category*	*Maximum permissible Legionella concentration in the water of the tank:*
low	Single-family housing Residential apartment building without central hot water supply Administration Schools without showers Sale Restaurants	5×10^5 cfu/l

	Meeting rooms Stores, repositories	
medium	Residential apartment building with central hot water supply Schools with showers Sport facilities, indoor and outdoor pools Hotels, military barracks	5 x 10^3 cfu/l
high	Hospitals, particularly transplant departments and / or special departments (oncology, haematology, etc.) Housing for elderly and disabled people, prisons	Not detectable – in practice usually less than 100 cfu / L NOTE: these applications are not considered in this report (see paragraph 3.1.3)

3.3 Results of model calculations

3.3.1 Typical occurrences of temperatures in the tank

With reference to table 3, four temperature ranges in the heat storage tank are of interest:

- <25 °C: no growth
- 25 – 47 °C: growth
- 47 – 55 °C: no growth
- > 55 °C: Disinfection

Typical temperature occurrences in the tank are illustrated in figure 2. The northern region, as opposed to the southern region, shows a more frequent occurrence of the no growth and growth situations and a less frequent occurrence of disinfection temperatures. The middle region does not differ much from the northern region. In all cases, the growth temperature region is populated frequently.

A low V/A's, opposed to a high V/A, induces more frequent disinfection temperatures.

3.3.2 Typical fluctuations of the legionella concentration in the tank

Based on the rules of table 3, the legionella concentration in the water of the tank is calculated over a two year period.

In general the legionella concentration builds up slowly with time, can be stable during some time, and will decrease fast when disinfection temperatures are experienced.

A typical annual pattern of legionella concentration in the tank shows a high legionella concentration during the months: November, December and January and a low concentration during the summer months.

The northern region, opposed to the southern region, show on average a higher legionella concentration.

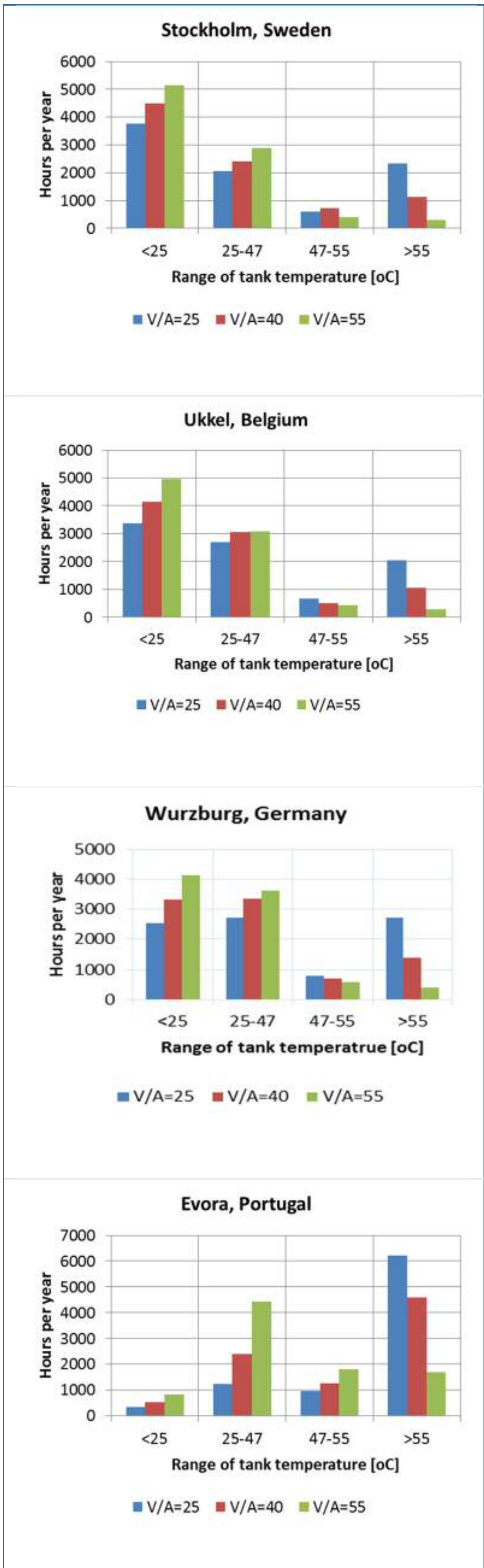


Figure 2 Typical distributions of the tem-
peratures in the tank for the reference

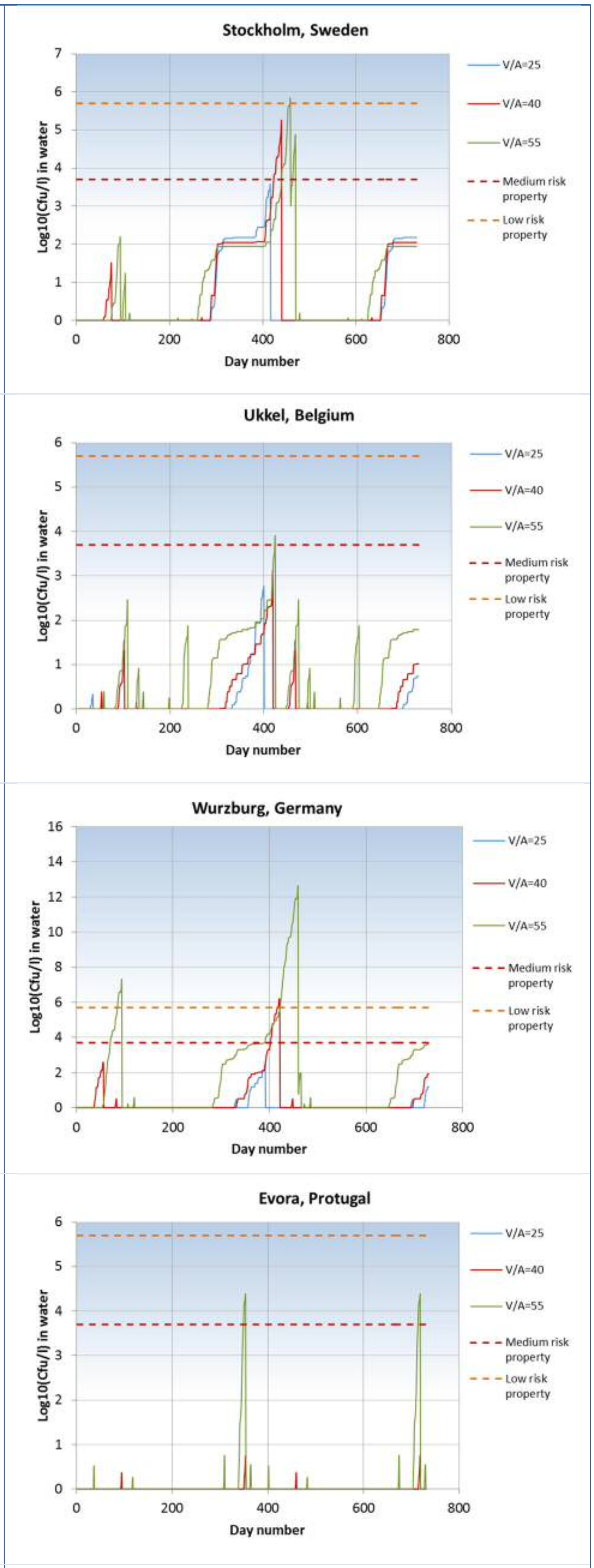


Figure 3 Typical fluctuations of the population of
legionellae in the water of the tank for the refer-

preheat system.	ence preheat system.

3.3.3 Typical pattern of exceedence of the risk levels

In Table 4 above two risk limits are defined for low and medium risk applications. The annual total time during which these limits are exceeded are an indicator of the risk from legionellae. Figure 4,figure 5 andfigure 6 illustrate this for the reference preheat system.

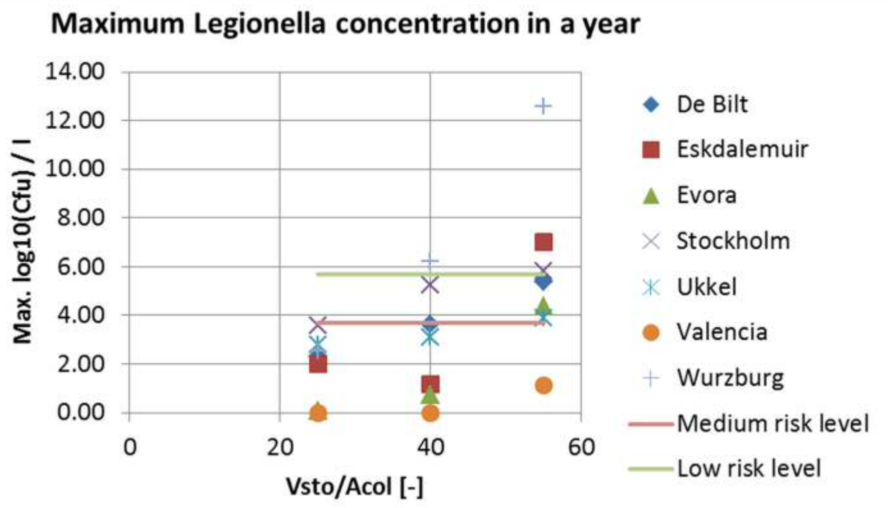


Figure 4 Typical pattern of the total annual time when the risk levels are exceeded.

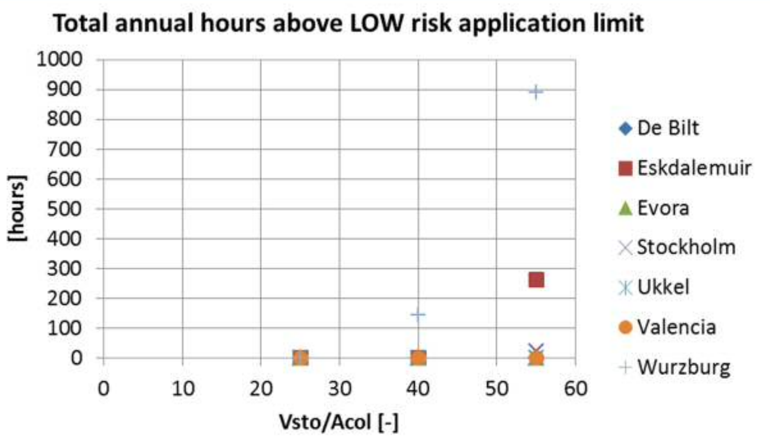


Figure 5 Typical pattern of the total time when the low risk level is exceeded annually.

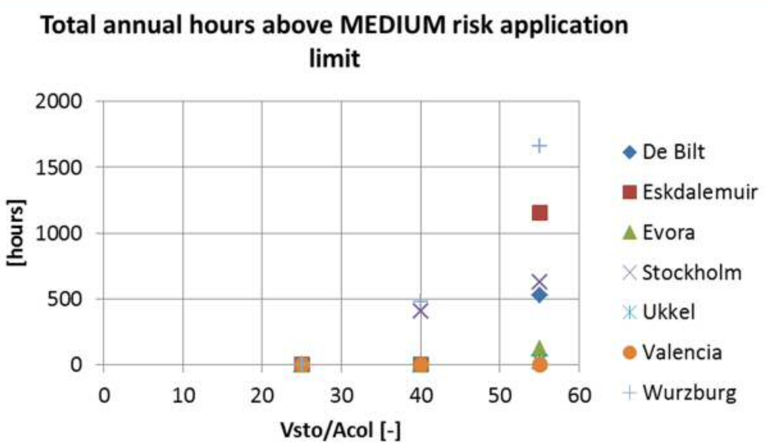


Figure 6 Typical pattern of the total time when the medium risk level is exceeded annually.

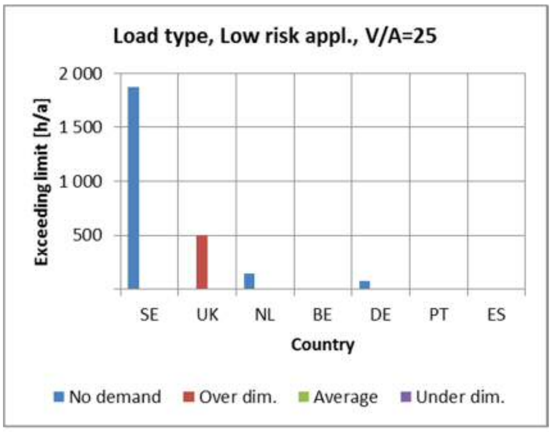
Typically the limits are less often exceeded with system designs based on low values of V/A (large collector area, small tank volume) and more frequently exceeded with high values of V/A.

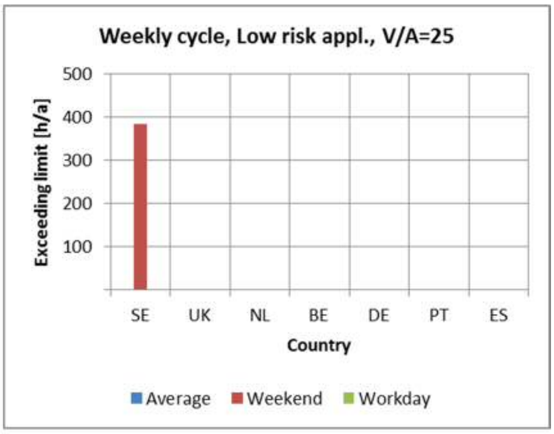
Since the limit for medium risk applications is lower than for low risk applications, the duration of this exceedence is longer for medium risk applications.

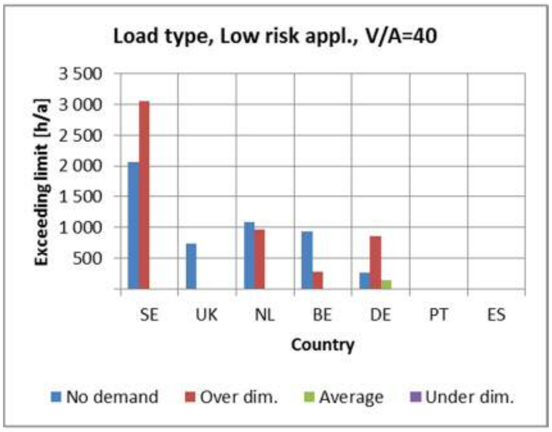
The exceedence of a limit occurs mostly once a year, but may occur several times a year.

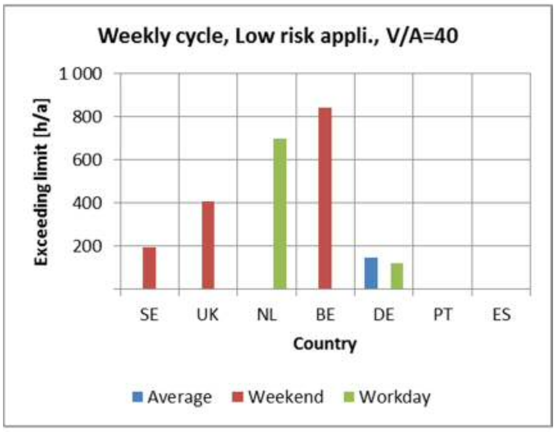
3.3.4 Results of all calculations

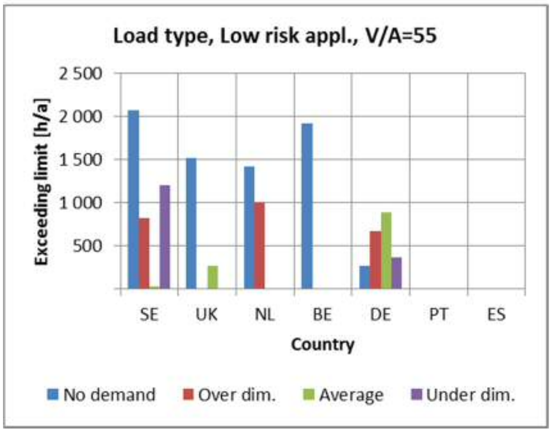
The results of all calculations for preheat systems are presented in the number of hours a limit is exceeded and are presented in figure 7 and figure 8. The results for the solar-only systems are presented in figure 9 and figure 10.

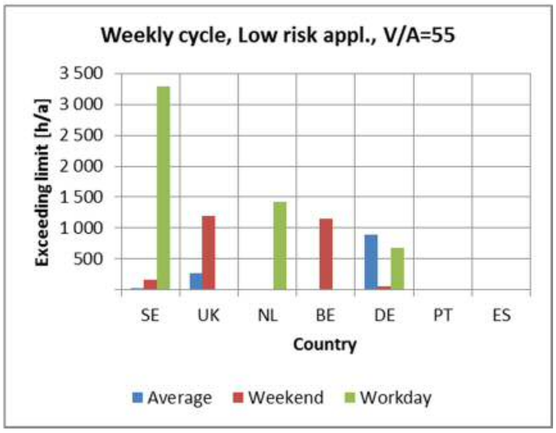

Load type, Low risk appl., V/A=25
2 000
1 500
1 000
500
Exceeding limit [h/a]
SE UK NL BE DE PT ES
Country
No demand Over dim. Average Under dim.


Weekly cycle, Low risk appl., V/A=25
500
400
300
200
100
Exceeding limit [h/a]
SE UK NL BE DE PT ES
Country
Average Weekend Workday


Load type, Low risk appl., V/A=40
3 500
3 000
2 500
2 000
1 500
1 000
500
Exceeding limit [h/a]
SE UK NL BE DE PT ES
Country
No demand Over dim. Average Under dim.


Weekly cycle, Low risk appli., V/A=40
1 000
800
600
400
200
Exceeding limit [h/a]
SE UK NL BE DE PT ES
Country
Average Weekend Workday


Load type, Low risk appl., V/A=55
2 500
2 000
1 500
1 000
500
Exceeding limit [h/a]
SE UK NL BE DE PT ES
Country
No demand Over dim. Average Under dim.


Weekly cycle, Low risk appl., V/A=55
3 500
3 000
2 500
2 000
1 500
1 000
500
Exceeding limit [h/a]
SE UK NL BE DE PT ES
Country
Average Weekend Workday

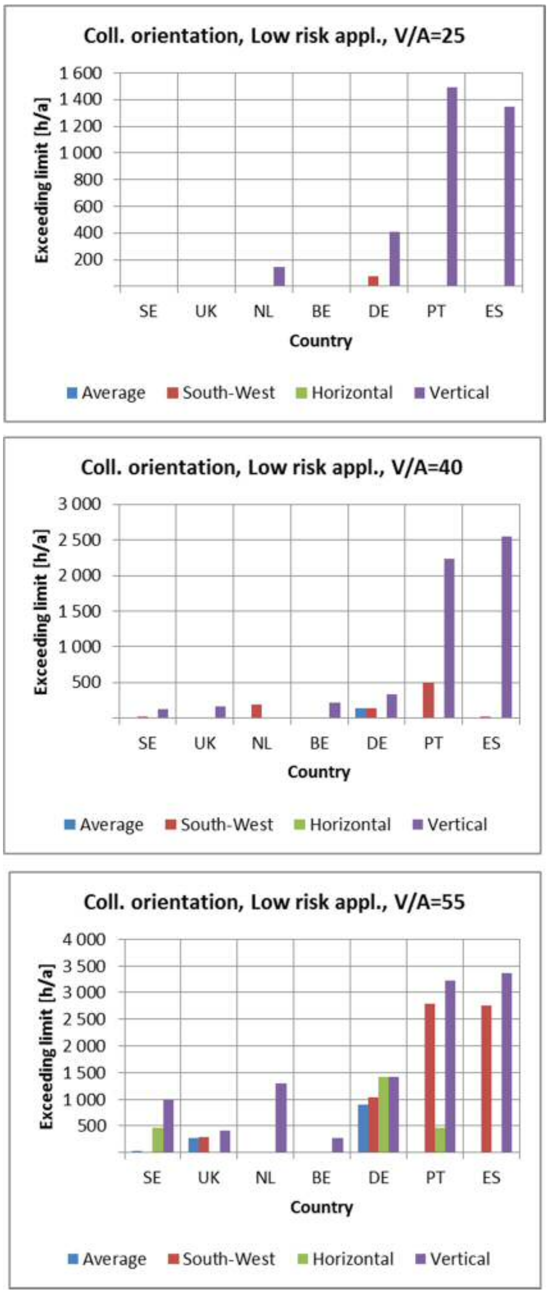
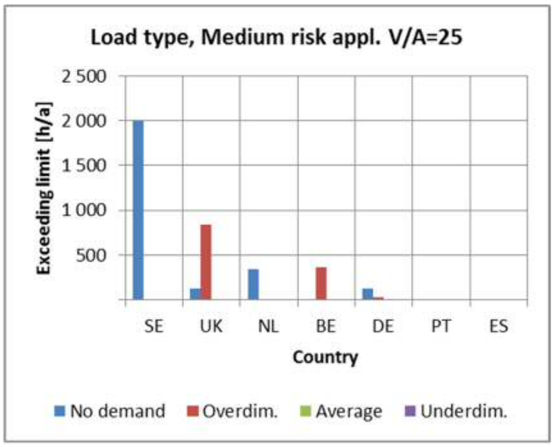
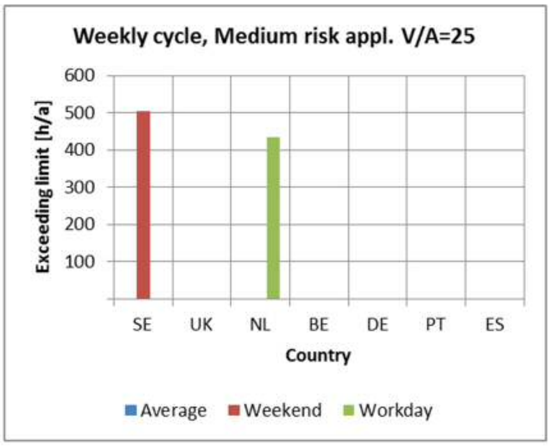
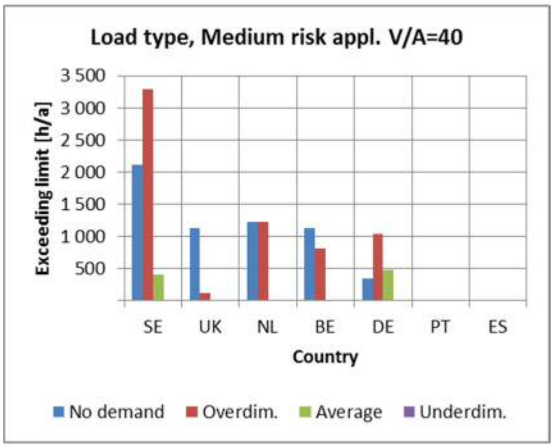
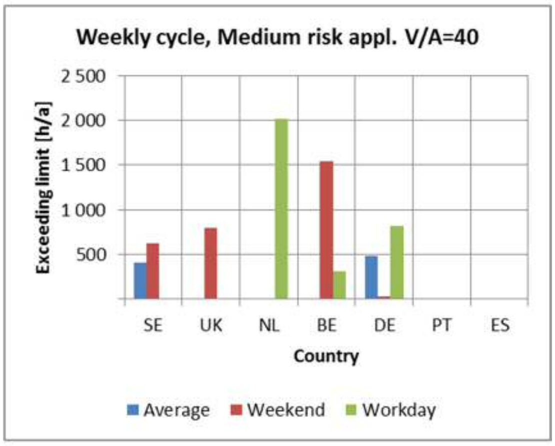


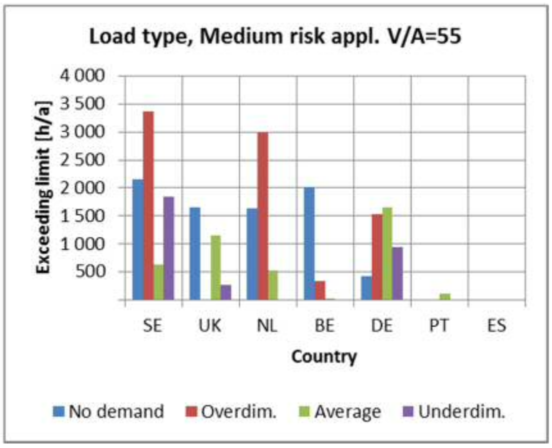
Figure 7 Results for a pre-heat system, expressed in hours exceeding the limit for low risk applications.

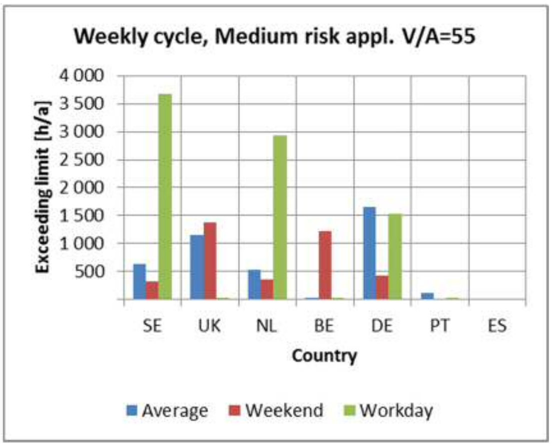

Load type, Medium risk appl. V/A=25
Exceeding limit [h/a]
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand
Overdim.
Average
Underdim.


Weekly cycle, Medium risk appl. V/A=25
Exceeding limit [h/a]
600
500
400
300
200
100
SE UK NL BE DE PT ES
Country
Average
Weekend
Workday


Load type, Medium risk appl. V/A=40
Exceeding limit [h/a]
3 500
3 000
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand
Overdim.
Average
Underdim.


Weekly cycle, Medium risk appl. V/A=40
Exceeding limit [h/a]
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
Average
Weekend
Workday


Load type, Medium risk appl. V/A=55
Exceeding limit [h/a]
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand
Overdim.
Average
Underdim.


Weekly cycle, Medium risk appl. V/A=55
Exceeding limit [h/a]
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
Average
Weekend
Workday

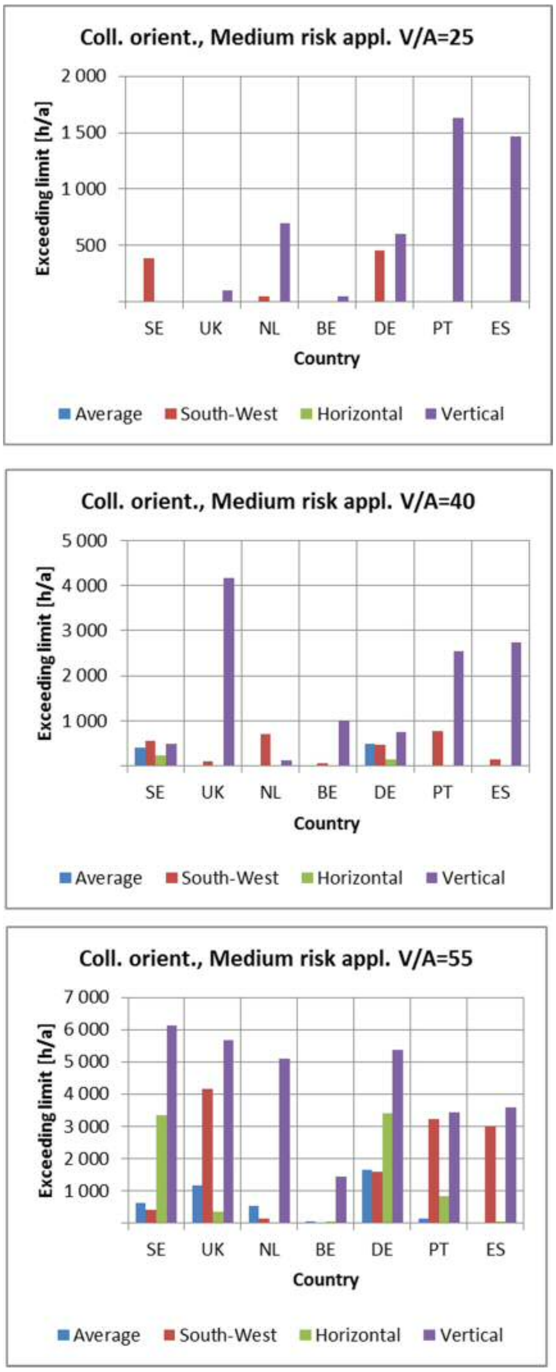


Figure 8 results for a pre-heat system, expressed in hours exceeding the limit for medium risk applications.

Results for Pre-heat systems

** Southern European regions*

In southern European regions the limits are not exceeded except in the situation where there is suboptimal orientation of the collector. This is especially true for a vertically mounted collector which causes the limits to be exceeded for 20% to 30% of the year for all V/A's. For a south-west oriented collector this is also noted but to a lesser extent for a V/A=55.

** North and middle European regions*

The results for north and middle European regions do not differ much.

In general, the duration when limits are exceeded increases when the tank volume increases compared to the annual heat demand. The ultimate condition with no heat demand produces the longest periods when limits are exceeded. Average and under dimensioned tanks with a V/A ≤ 40 show no or minor exceedence of the limits.

A non-continuous daily use of hot water (weekend or workday use only) shows an increase in the duration of the exceedence of the limits. This effect is stronger for weekend use compared to workday use. For systems with a V/A ≤ 25 the total time exceeding the limits is relatively small.

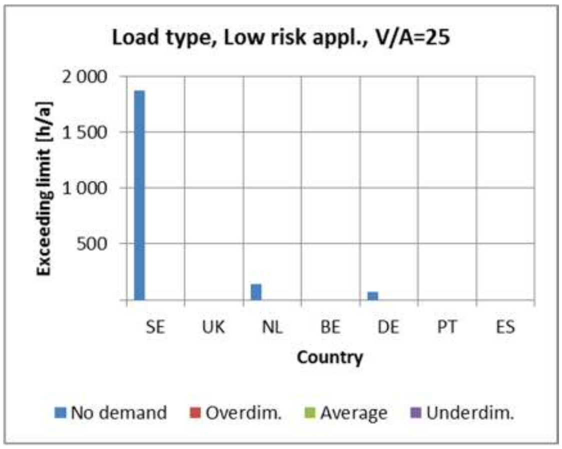
A non-optimal orientation of the collector, and especially for a vertically mounted collector, shows an increase in the duration of the exceedence of the limits. This effect is relatively small for systems with a V/A ≤ 40, although the UK shows a single peak at V/A=40.

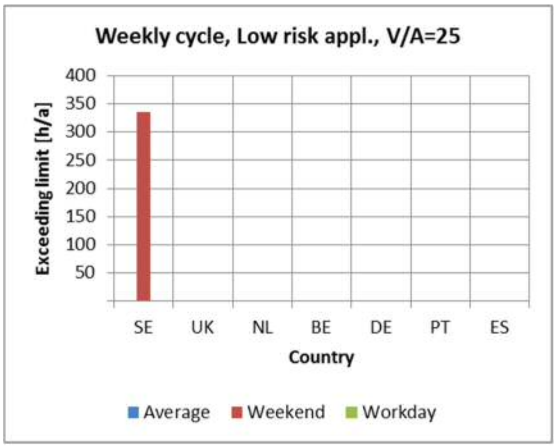
** Low and medium risk applications*

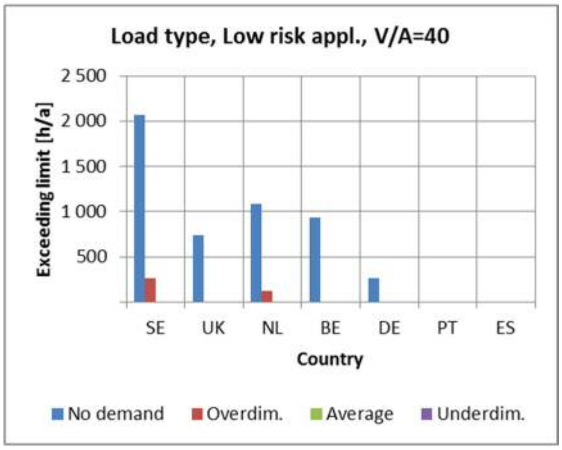
Although the number of occurrences when the limits are exceeded, and the duration thereof, increases for medium risk applications, the results are much the same.

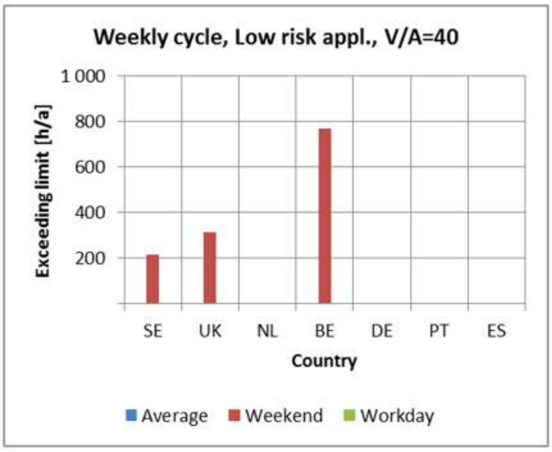
** Uncertainties*

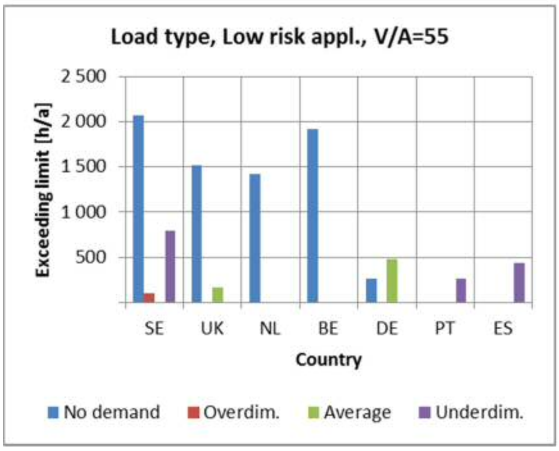
It should be noted that occasionally unexpected results are noted.

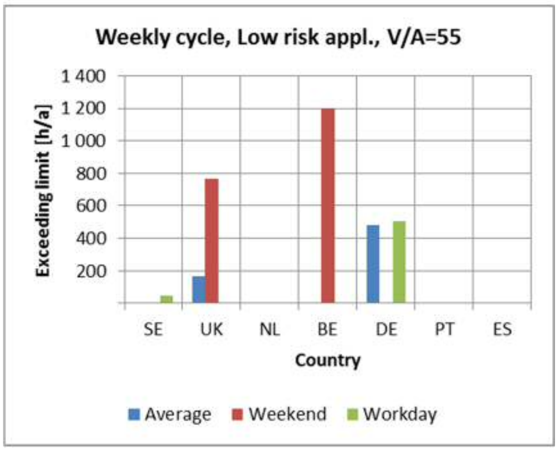

Load type, Low risk appl., V/A=25
Exceeding limit [h/a]
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand Overdim. Average Underdim.


Weekly cycle, Low risk appl., V/A=25
Exceeding limit [h/a]
400
350
300
250
200
150
100
50
SE UK NL BE DE PT ES
Country
Average Weekend Workday


Load type, Low risk appl., V/A=40
Exceeding limit [h/a]
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand Overdim. Average Underdim.


Weekly cycle, Low risk appl., V/A=40
Exceeding limit [h/a]
1 000
800
600
400
200
SE UK NL BE DE PT ES
Country
Average Weekend Workday


Load type, Low risk appl., V/A=55
Exceeding limit [h/a]
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand Overdim. Average Underdim.


Weekly cycle, Low risk appl., V/A=55
Exceeding limit [h/a]
1 400
1 200
1 000
800
600
400
200
SE UK NL BE DE PT ES
Country
Average Weekend Workday

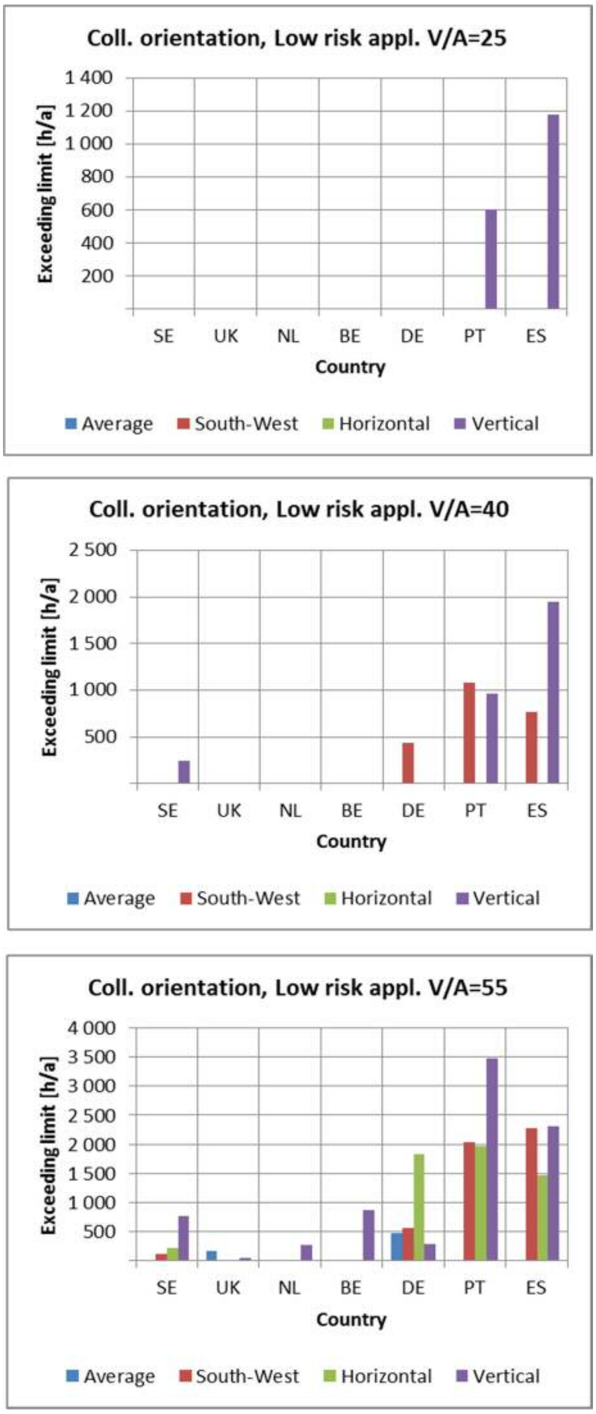
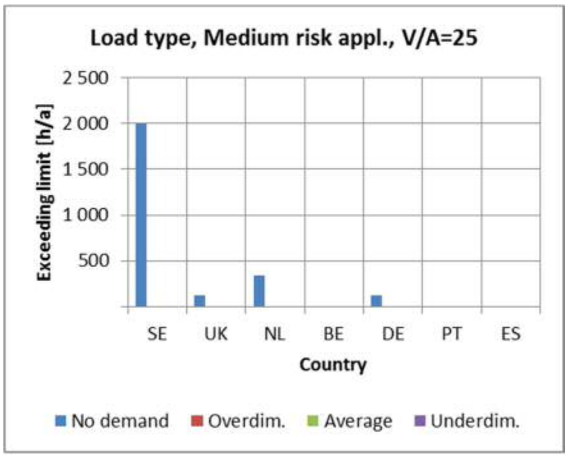
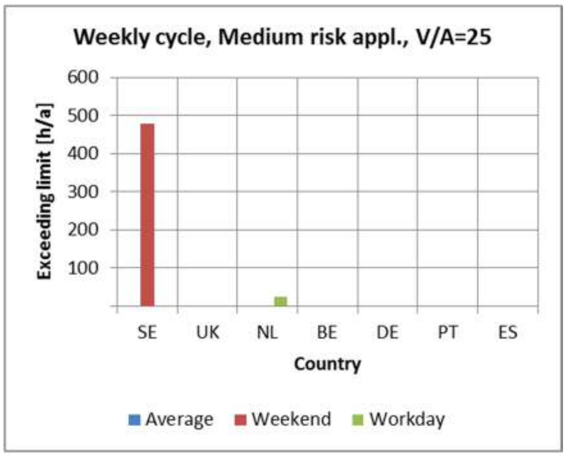
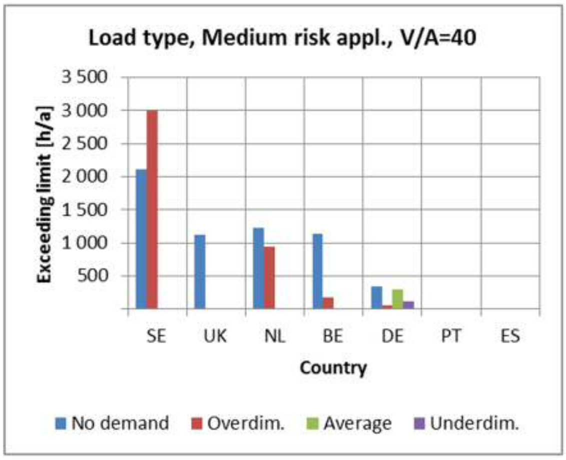
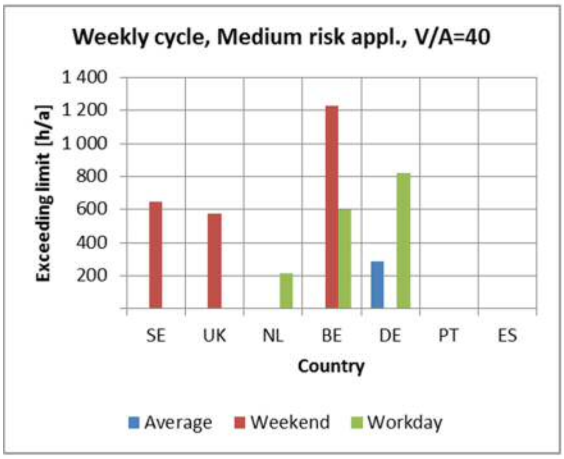


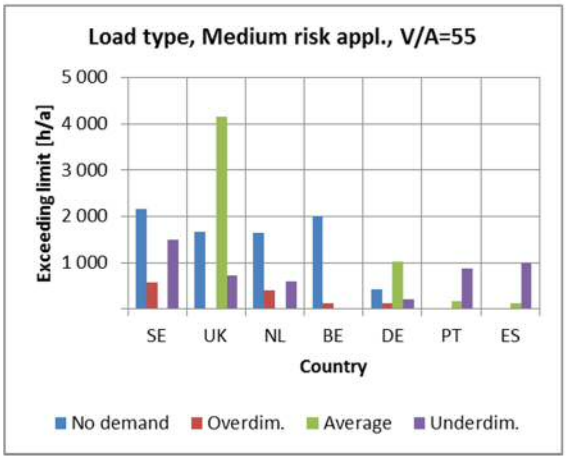
Figure 9 Results for a solar-only system, expressed in hours exceeding the limit for low risk applications

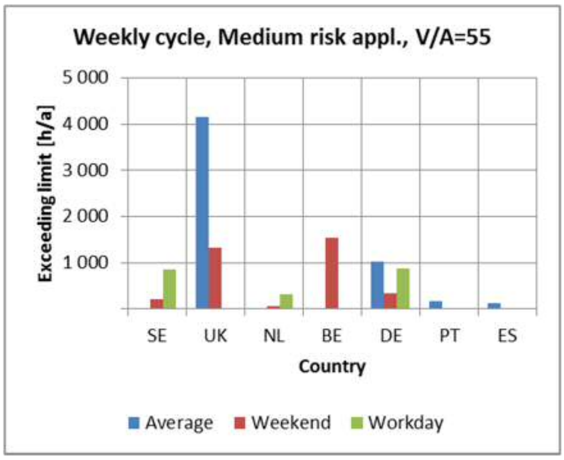

Load type, Medium risk appl., V/A=25
Exceeding limit [h/a]
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand Overdim. Average Underdim.


Weekly cycle, Medium risk appl., V/A=25
Exceeding limit [h/a]
600
500
400
300
200
100
SE UK NL BE DE PT ES
Country
Average Weekend Workday


Load type, Medium risk appl., V/A=40
Exceeding limit [h/a]
3 500
3 000
2 500
2 000
1 500
1 000
500
SE UK NL BE DE PT ES
Country
No demand Overdim. Average Underdim.


Weekly cycle, Medium risk appl., V/A=40
Exceeding limit [h/a]
1 400
1 200
1 000
800
600
400
200
SE UK NL BE DE PT ES
Country
Average Weekend Workday


Load type, Medium risk appl., V/A=55
Exceeding limit [h/a]
5 000
4 000
3 000
2 000
1 000
SE UK NL BE DE PT ES
Country
No demand Overdim. Average Underdim.


Weekly cycle, Medium risk appl., V/A=55
Exceeding limit [h/a]
5 000
4 000
3 000
2 000
1 000
SE UK NL BE DE PT ES
Country
Average Weekend Workday

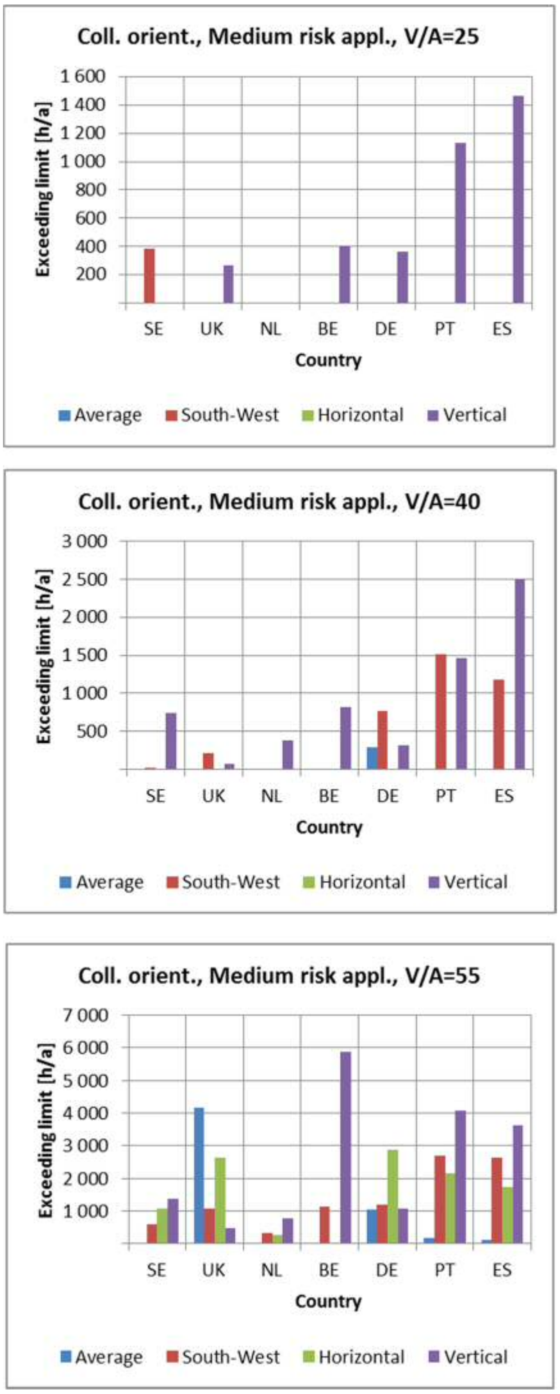


Figure 10 Results for a solar-only system, expressed in hours exceeding the limit for medium risk applications.

Results for solar-only systems

The results for solar-only systems do not differ much from those of pre-heat systems, although it should be noted that in general less exceedence of the limits is indicated.

3.4 Evaluation

The concentration of legionellae in the water of the heat storage tank is a good parameter to estimate the risk from legionellae added to the hot water system by a solar water heater. The duration of an exceedence of the limit for a low or medium risk application of the concentration of legionella in the water, is a good measure to estimate the risk from legionellae.

The calculated fluctuations in the legionella concentrations are based on worst-case assumptions.

a) *It is assumed that the complete inner wall is populated with legionellae.*
   Depending on the materials used and the finishing of the inner wall it may well be that legionella colonies are mostly restricted to irregularities on the inner wall, like internal screw joints, weld seams, the inspection hatch, anode or limestone deposits at the bottom. As a consequence the growth area for legionellae will be significantly smaller [4], resulting in a much lower legionella concentration in the water. In the majority of cases the heat storage tank is made of stainless steel, copper or enamelled steel, that is known from literature to be a bad host for legionella colonies.

b) *It is assumed that the average temperature in the tank is decisive for the fluctuations in the population of the legionellae on the inner wall.*

   The temperature stratification in the tank may well be such that the bottom is at the cold water temperature and the top above 60 ^{o}C. The average temperature is then within the legionella growth conditions, while in fact there is no growth at the lower part and disinfection at the top part of the tank.

c) *It is assumed that the tank is filled with potable water.*
   As a consequence the water velocity, over the inner surface, is too low to influence the legionella colonies on the inner wall. When, on the other hand, an internal heat exchanger filled with potable water is applied, the water velocity over the inner surface can be high enough to influence the legionella colonies on its wall and lower the legionella concentration significantly [5].

Although it is theoretically possible to apply a heat storage tank made from a non-optimal material, with a bad finish, no temperature stratification and filled with potable water, this extreme combination will seldom be the case. When drawing conclusions on the risk from legionellae based on the duration of the exceedence of the limits, this should be taken into consideration.

The results are to be seen as a worst-case analysis, showing qualitative assessments.

3.4.1 Effect of load type and weekly cycle

The pattern of use of hot water has a strong influence on the time exceeding the limits. When a system is not used daily during a weekly cycle (only weekends or workdays), the system shows increased periods when the limits are exceeded.

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[4] For a 150 litre heat storage tank the vulnerable area is estimated at 3% of the total inner area.

[5] For a 150 litre heat storage tank the surface area of a heat exchanger is estimated ar 25% of the total inner area of the tank.

In single family applications the pattern of use of hot water is highly unpredictable and can change during the lifespan of the solar water heater from very intensive to almost seldom used.

In multifamily applications this effect weakens resulting in a more stable and continuous use pattern that will lead to less exceedence of the limits.

The worst-case situation of no heat demand cannot realistically be the baseline for establishing the boundary conditions for a Legionella-safe solar water heater. A practical way out is to issue a warning to the owner / user of the system stating that the system may become vulnerable to legionella growth when the heat demand is significantly smaller than the design conditions. In those cases the collector pump could be switch off during the November, December and January or the tank should be heated up weekly to 55 ^{o}C for 2 hours minimum for low and medium risk applications [6].

3.4.2 Orientation of the collector

The orientation of the collector is of great influence on the risk from legionellae. In particular a vertical tilted collector in a southern European region will not pass any realistic legionella safety criteria. A vertically mounted collector should not be permitted in these regions. To a lesser extent this is also the case for a south-west or worse orientation.

In north and middle European regions this effect is also noted, but to a lesser extent.

3.4.3 Design of the solar water heater

Oversizing the volume of the tank compared to the design heat demand conditions should be prevented. The tank volume should be smaller or equal to the daily hot water usage (l/day).

The ratio V_{sto}/A_{col} (=V/A) is of great influence on the risk from legionellae. A low V/A (large collector area compared to tank volume) shows minor exceedence of the limits and as a consequence less vulnerability to legionella growth.

A low V/A forces the tank to achieve more frequent disinfection temperatures than a high V/A. On the other hand a high V/A forces the tank to a lower temperature than a low V/A. The influence of frequent disinfection appears to affect the total balance of growing and dying more than frequent low temperatures.

For southern European regions, with a reasonably well orientated collector, the V/A can be equal or smaller than 55.

In north and middle European regions for systems with a non-optimal collector orientation or a non-continuous daily use, the V/A should be equal to or smaller than 25. In more optimal conditions the V/A could be equal to or smaller than 40.

3.4.4 Preheat system versus solar-only

Due to the fact that solar-only systems are not equipped with an auxiliary heater, the hot water is used on average at a lower (demand) temperature. Assuming that the same heat is needed in both solar-only and pre-heat systems, this means that solar-only systems effectively show a higher water throughput. This effect is comparable with a pre-heat system with an under dimensioned tank volume, implying a lesser vulnerability to the development of high concentrations of legionellae in the tank.

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[6] During these months only a minor part of the annual energy output is realized. Switching off the pump will not have a very significant effect on the annual energy output.

An alternative strategy could be to switch the pump off during these months only when the tank temperature exceeds 25 ^{o}C. This will minimize the negative effects on the annual energy output of the solar water heater.

The absence of an auxiliary heater makes a solar-only system more vulnerable to legionellae while due to the higher annual water throughput, this risk is decreased. Overall it is reasonable to apply the same rules to a solar-only system as to preheat systems.

3.4.5 Low and medium risk applications

The duration of periods of exceedence of the medium risk application limit is longer than for low risk applications. The extent of the difference is not as big that different conclusions can be drawn for both application types. Nevertheless, considering hot water installation as a whole, it is important to make a distinction between low and medium risk applications.

3.4.6 Notes

The balance of growth and death of legionellae in the tank is a dynamic process governed by circumstances that are difficult to predict for individual situations. When several negative effects come together at a certain point in time, this may result in an unexpected high legionella concentration in the tank.

Switching off the collector pump during November, December and January is a good measure to make all of the system designs and application modes legionella safe.

Flushing the heat storage tank when legionellae are expected, is not a secure way to make the solar part of the system safe again. Up to 98% of the Legionella on the inner wall will still remain.

Bypassing the heat storage tank during the winter months is not a secure way to make the system legionella-safe. In contrast, this will make the system less safe.

4 Conclusions

In a solar heat storage tank legionellae can grow and die. The balance between both is a dynamic and complex process involving climate, system design, the collector orientation, the way the solar water heater is used and maintained [7]. By applying the following rules in the application of a solar water heater, the risk from legionellae will be minimized.

4.1 Design rules

a) use materials in accordance with national and European standards for materials being in contact with potable water (2002/359/EG and national implementations thereof);
b) use materials and inner surface finishing of the heat storage tank in conformity with the requirements in use in the food industry;
c) the following materials are recommended: stainless steel, copper or enamelled steel;
d) design the solar water heater such that a large temperature stratification can be realised;
e) if an option, use a tank design with a heat exchanger filled with potable water;

4.2 Restrictions to the application

f) choose a tank volume smaller or equal to the design heat demand conditions in l/day;
g) prevent a vertical tilt of the collector or azimuth of the collector beyond south-west / south-east, especially in the southern European regions;
h) formulate an explicit warning to the user of the system stating that the system becomes vulnerable to legionellae when seldom used;
i) Choose a V_{sto}/A_{col} (=V/A) of the system according to:

when none of the above rules are implemented or there is an expectance of undefined heat load:	V/A ≤ 25
When none of the above rules are implemented, but the collector has an optimal orientation, then:	
– North and middle European regions:	V/A ≤ 40
– Southern European regions:	V/A ≤ 55
All of the above rules are implemented:	V/A ≤ 55

[7] It is noted that especially the regular cleaning of deposits from the bottom of the tank will decrease the potential area for Legionella growth. This type of maintenance can be effectively implemented in larger tanks via an inspection hatch.

5 Proposals for further research

There is a need for a carefully designed broad field study aimed at determining the frequency of occurrence of legionellae in hot water systems and especially systems including renewable energy sources in comparison with conventional hot water systems of otherwise similar characteristics in terms of age, complexity, design and construction materials. This should be a comprehensive study covering a representative part of Europe and most of the different types of hot water systems. A limited sized study is not recommended, since this may well cause more uncertainty than the one we are now experiencing.

The study may be financed by one of the European research programs (e.g. IEEE).

There is also a need for a trial of heat and other disinfection regimes using plumbing test rigs incorporating solar water heaters and colonised with legionellae under natural conditions. This study should investigate the need for frequent heating to 60 ºC to control legionellae in such systems.

Due to practical reasons, this simulation model study was limited in the scope. In a further study the scope could broadened to:

- solar heat storage tanks with a combined function of storing both solar heat and heat from an auxiliary heater;
- solar heat storage tanks with an integrated heat exchanger containing potable water;
- solar water heaters for a combined function of water heating and space heating.
- Load side heat exchanger in a solar water heating system.

As mentioned in chapter 3.4 b) the effect of temperature stratification in the tank can be of great influence on the fluctuations in the population of legionellae. In a further extended study, this effect could be included.

When more (quantifiable) information on the rate of growth and death of legionellae in a water tank becomes available, the study could be repeated for more accurate results.

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