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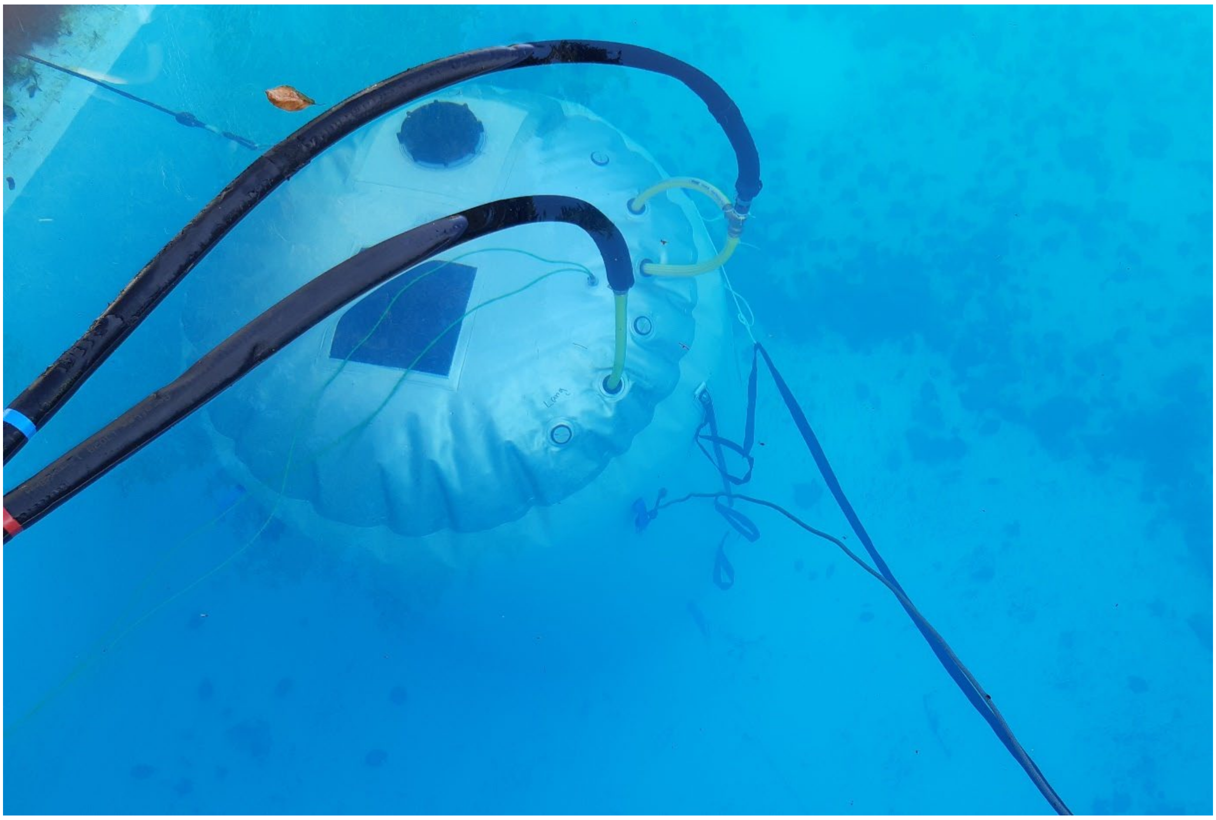
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

Final report dated 15 December 2023

SOUR Call 1-2021

BILS

Bubble in the lake storage



Source: A. Bohren

sweet swiss energy research for the energy transition

Date: 15 December 2023

Location: Rapperswil

INSTITUT FÜR
SOLARTECHNIK

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Project start – end: 10.2021 – 11.2023

Subsidy recipient:
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SFOE contract number: SI/502276-01

Table of Contents

Abbreviations

BILS	Bubble in the lake storage
PU	Polyurethane
SAP	Superabsorbent material

Summary

Storing heat as hot water in large storage reservoirs is the most straightforward technology for seasonal storage and for stabilizing district heating networks. Large thermal storage systems are known in different variants, and seasonal storage efficiencies of more than 90% have been reported. However, the required space is usually not available close to cities in Switzerland. The goal of this project is to investigate the practical feasibility of placing large thermal storages made of flexible envelopes in lakes ("Bubble In the Lake Storage", BILS). The main conceptual ideas for this approach are the following:

- Hot water is stored using a foil that is separating the hot area (storage) from the lake.
- Environmental damage is not a critical issue, as only water is stored inside the lake water.
- Lakes provide sufficient space close to inhabited areas while avoiding use of land.

In this project the general technical feasibility of the concept is investigated to provide a basis for the decision whether this approach is technically viable and shall be further worked on or not. The main work consists in literature studies, physical considerations on thermal insulation and static behaviour, experiments to confirm and test ideas for the realisation of such storages, and expert interviews.

The most important result is that the realisation of BILS is possible. Thermal insulation is a key issue for which an innovative solution has been found that is also compatible with the requirement for buoyancy management. However, before a pilot system can be started, a number of issues still need to be developed further, some of which are already planned in a follow-up project.

Résumé

Stocker de la chaleur sous la forme d'eau chaude contenue dans de grands réservoirs est la technologie la plus simple pour le stockage saisonnier et pour la stabilisation des réseaux de chauffage à distance. Différentes variantes de grands systèmes de stockage de chaleur sont connues, et des rendements de stockage saisonnier de plus de 90 % sont rapportés. Cependant, l'espace nécessaire à proximité des villes n'est généralement pas disponible en Suisse. Le but de ce projet est d'étudier la faisabilité technique de placer de grands réservoirs thermiques, constitués d'enveloppes flexibles, dans des lacs ("Bubble In the Lake Storage", BILS). Les principales idées conceptuelles sont les suivantes :

- L'eau chaude est stockée à l'aide d'une fine feuille qui sépare la zone chaude (stockage) du lac.
- Les dommages environnementaux ne sont pas un problème critique, car ce n'est que de l'eau qui est stockée à l'intérieur de l'eau du lac.
- Les lacs offrent, à proximité des zones habitées, un espace suffisant qui n'est pas disponible sur la terre ferme.

Dans ce projet, la faisabilité technique générale du concept est étudiée afin de fournir une base pour la décision de savoir si cette solution est viable du point de vue technique et si elle doit être poursuivie ou non. Le travail principal consiste en des études de littérature, des considérations physiques concernant principalement l'isolation thermique et le comportement statique, des expériences pour confirmer et tester les idées pour la réalisation de tels stockages, et des interviews avec des experts.

Le résultat le plus important est que la réalisation de BILS est possible. L'isolation thermique est une question centrale pour laquelle une solution innovante a été trouvée, qui est également compatible avec l'exigence de gestion de la poussée hydrostatique. Cependant, avant de procéder à la mise en place d'un système pilot, il reste encore un certain nombre de points à approfondir, dont certains sont déjà prévus dans le cadre d'un projet subséquent.

Zusammenfassung

Die Speicherung von Wärme in Form von Warmwasser in grossen Behältern ist die einfachste Technologie zur saisonalen Speicherung und zur Stabilisierung von Fernwärmenetzen. Grosse thermische Speicher sind in verschiedenen Varianten bekannt, und es wurden schon saisonale Wirkungsgrade von über 90% nachgewiesen. Der benötigte Platz ist jedoch in der Schweiz in der Nähe von Städten nicht verfügbar. Ziel dieses Projekts ist es, die praktische Machbarkeit von grossen Wärmespeichern zu untersuchen, die aus flexiblen Hüllen in Seen bestehen ("Bubble In the Lake Storage", BILS). Die wichtigsten konzeptionellen Ideen für diesen Ansatz sind die folgenden:

- Heisses Wasser wird innerhalb einer Folie gespeichert, die den heissen Bereich vom See trennt.
- Umweltschäden sind kein kritisches Thema, da nur das Wasser im See gespeichert wird.
- Seen bieten Platz in der Nähe von bewohnten Gebieten, ohne dass Land genutzt werden muss.

In diesem Projekt wird die allgemeine technische Machbarkeit des Konzepts untersucht, um eine Grundlage für die Entscheidung zu schaffen, ob dieser Ansatz umsetzbar ist und weiter bearbeitet werden soll oder nicht. Die Arbeit besteht vor allem aus Literaturstudien, physikalischen Überlegungen zur Wärmedämmung und zum statischen Verhalten, Experimenten zur Bestätigung und Erprobung von Ideen für die Realisierung solcher Speicher sowie aus Experteninterviews.

Das wichtigste Ergebnis ist, dass die Verwirklichung von BILS möglich ist. Die Wärmedämmung ist aber ein zentrales Thema, für das eine innovative Lösung gefunden wurde, die auch mit den Anforderungen zur Kontrolle des Auftriebs vereinbar ist. Bevor jedoch eine Pilotanlage gebaut werden kann, müssen noch eine Reihe von Fragen weiterentwickelt werden, von denen einige bereits für ein Folgeprojekt vorgesehen sind.

Riassunto

L'accumulo di calore in grandi serbatoi è la tecnologia più semplice per lo stoccaggio stagionale e la stabilizzazione delle reti di teleriscaldamento. Sono già note diverse tipologie di grandi accumulatori termici per i quali si sono registrati rendimenti stagionali superiori al 90%. In Svizzera, tuttavia, le aree necessarie in prossimità dei centri abitati non sono generalmente disponibili. L'obiettivo di questo progetto è studiare la possibilità di collocare nei laghi grandi serbatoi di accumulo di calore costituiti da involucri flessibili ("Bubble In the Lake Storage", BILS). L’approccio si basa sulle seguenti idee concettuali:

- L’acqua calda è accumulata utilizzando una sottile pellicola che separa la zona calda dal lago.
- L’impatto ambientale è sostanzialmente nullo, poiché nel lago viene immagazzinata solo acqua.
- I laghi forniscono spazio sufficiente vicino alle zone abitate, che altrimenti non sarebbe disponibile.

In questo progetto si analizza la fattibilità tecnica generale del concetto, al fine di fornire una base per decidere se questo approccio sia tecnicamente fattibile e possa essere perseguito. Il lavoro principale consiste in studi di letteratura, considerazioni fisiche soprattutto sull'isolamento termico e sul comportamento statico, esperimenti per confermare e testare le idee per la realizzazione di questi serbatoi di accumulo e interviste con esperti.

Il risultato più importante è che la realizzazione di BILS è possibile. L'isolamento termico è un aspetto cruciale per il quale è stata trovata una soluzione innovativa, compatibile anche con i requisiti di gestione della spinta di galleggiamento. Tuttavia, prima di poter avviare un impianto pilota è necessario analizzare e sviluppare ulteriormente diversi altri aspetti, alcuni dei quali sono già previsti in un progetto successivo.

1 Introduction

1.1 Context and state of the art of research

Large thermal energy storages for district heating systems are known in different variants. All aspects such as the construction, the integration in the networks, the modes of operation and the related thermal performances, but also financial aspects or environmental impacts have been investigated in many projects [1],[2],[3]. The general principles of large storages and their integration into district heating systems are therefore well known and there are experts, companies and realized projects, mainly in Denmark and Germany. There is also a growing interest in large district heating system in Switzerland and all over Europe [4],[5]. One of the relevant components in most of these systems is a heat storage, either to compensate temporary fluctuations in a multivalent network and/or to support seasonal heat storage. Remarkably high seasonal storage efficiencies of more than 90% have been reported for conventional pit storages in Denmark, but also much lower values are known [6]. Apart from the thermal performance, there are still various technical and technological challenges such as for example the make and construction of the top lid, managing the water quality in the storage, corrosion, lifetime of the liners, optimal operation modes, etc. where research projects and developments are ongoing [7],[8].

One of the main advantages of large heat storages is the ratio between surface and volume that is becoming more and more advantageous in terms of thermal losses with increasing storage size. The thermal isolation of the outer skin is becoming hence less and less relevant the bigger the storage size. Indeed, standard pit storages are built without additional side insulations, the environmental ground being the only insulation.

To the author’s best knowledge, there are no investigations available on the accommodation of large thermal storages inside standing body of water (see also chapter 4.2 Literature studies). Some of the results of existing research on conventional big thermal storages is for sure relevant also for BILS, but there is no specific research or expertise available.

1.2 Unconventionality and originality of the project

Latent thermal storages are commonly associated with big steel tanks or with large pits either underground or on the ground. In this project the option is investigated to locate big storages in standing waters (in Switzerland this means in lakes). The basic idea of the bubble-in-the-lake-storage (BILS) concept is that the mantel of a storage does not necessarily have to be a stiff and strong envelope but can be flexible as well, probably similar to a jelly fish. If such a water filled flexible device (the bubble) is in standing water, it can be assumed that the static behaviour is mainly defined by the surrounding water and not so much by the container itself. The mantel is only there to separate the storage from the lake. This allows using thinner flexible materials, hence reducing the use of materials, and hopefully also reducing costs. One goal of the approach is therefore also to establish a technology that is based on easily available low-cost materials.

The availability of very large thermal storage opens more options for district heating systems. Tank Thermal Energy Storages (TTES) are known in different variants and with volumes in the range of up to about 10'000 m^3. Pit thermal energy storages (PTES or Pit storages) are frequently used in Denmark and Germany in sizes up to something like 200'000 m^3, projects up to 1'000'000 m^3 are in preparation.

The BILS concept would presumably allow also for much bigger storages as there are virtually no static limits.

The availability of large storages is a key element in efficient district heating systems and can also be considered as a boosting requirement for solar thermal technologies.

As there is no previous work on this approach, the expected challenges were not known at the start of the project. The main objective of the project is therefore to provide a basis for future developments or, in the worst case, to find reasons why the idea should not be pursued further.

2 Objectives

Even if the approach looks simple at first sight, there are various basic technical questions that need response before pilot projects can be realized. The expected main outcome of the project is a feasibility assessment of the concept. The following main questions were intended to be tackled:

- Suitability of different BILS concepts with respect to their static and thermal behaviour.
- Materials for the storage skin and options to reduce thermal losses.
- Legal and environmental caveats
- Potential for Switzerland

As there is no experience at all in this field, the main focus is on the technical feasibility and on the technical behaviour of the storage. The following topics are explicitly not assessed in detail in this project:

- Thermal charging of BILS. Several options are thinkable such as solar thermal fields, heat pumps and similar. But this is not considered being in the scope of this proposal as it is not a specific topic for the BILS concept but a general question on how to integrate a storage in a thermal network.
- Integration of BILS in a system and additional use of BILS such as for example for district cooling.
- Cost of BILS. This is very much related to the system cost and the future development of a dedicated industry (production of the storage).

After the first experiments it became clear, that the thermal insulation of the storage is a fundamental issue that requires much more attention than expected. For this reason, the work plan was adjusted and other topics such as legal aspects were not treated with the intended intensity.

One of the main goals is the building of a prototype storage. For this purpose, the project partner Luft & Laune with experience in plastic structures in water is in the project team.

The expected result is the acquisition of sufficient knowledge about the technical requirements and the most important technical challenges of the concept. The concept should be analysed to such an extent that follow-up projects can be initiated. At worst, it would also be considered a good result if, for whatever reason, it turns out that the concept is not feasible and should not be followed up further.

Experimental work is a key element of this project. To better convey the findings and results, there are many photos included in this report.

3 Methodology

As there is no experience and no expertise for the concept, we had to start from scratch. Initially the plan was to build a small prototype to test under laboratory conditions or in a swimming pool, but then to go quickly to a bigger version to be placed in a lake. However, the first experiments with the small prototype (see chapter 4.8.1) have demonstrated clearly that thermal insulation is a major issue that must be solved before going to bigger experiments. In addition, a simplified model of the thermal losses of a cylindrical BILS was developed[1] that allows to compute the thermal losses and basically also the thermal performance for different insulation systems and thicknesses. As a result, the issue of thermal insulation has become much more central to this project than expected, and the work was organised in such a way that a solution to this problem could be found first.

The main goal remained however to answer the question whether the concept is technically feasible or whether some hurdles appear that would imperatively require to stop all further investigations.

To approach these questions, we used the following methods:

- Literature (including internet) studies,
- Experimental work,
- Simple calculation methods and physical considerations,
- Expert interviews in related technologies.

The most important work is the experimental work to gain experience and to familiarize with the potential behaviour of such a device. The prototypes that were used for the experimental work, were produced using the specific equipment (such as specialized sewing machines) by the project partners Luft & Laune (www.luftundlaune.ch), specialized in the creation, planning and production of inflatable custom-made products. The expertise of Luft & Laune as well as having on stock various materials, components, brackets, glues, ribbons, zips, etc. needed to produce prototypes was essential for the project. The measuring equipment, the electric heating and the hydraulic components were mostly provided by the SPF Institute for Solar Technology of the Eastern Switzerland University of Applied Sciences OST.

The outdoor experiments in water were made in the public swimming area “Zwischen den Hölzern” in Oberengstringen close to Zurich. The laboratory experiments were made at the OST – Ostschweizer Fachhochschule in Rapperswil. The experimental work on the prototypes was mostly done together by members of the SPF Institute for Solar Technology and of Luft&Laune.

Furthermore, a student semester project was carried out as part of this project (see section 4.8.7).

The idea has attracted a lot of interest from several sides. Many internal and external discussions and interviews with experts provided valuable contributions to the results presented in this report.

[1] https://www.bils.tech/thermalcalculus

4 Results and discussion

In the following chapters the work, results and findings are presented in individual sections which are basically isolated work packages that are not presented in a chronological order but more in a thematic order. Together they form the basis for the conclusions.

4.1 Potential in Switzerland

The potential for BILS is mainly depending on the availability of a standing water in the vicinity of a thermal network. The usability and advantage of a BILS is strongly depending on the operating temperature and on the availability and type of the heat sources. The most promising use cases are for sure 3^{rd} and 4^{th} generation heating grids operating at temperatures in the range below 100 °C. Figure 1 shows an overview of the thermal networks in Switzerland. Currently there are more than 1000 thermal networks accounting for more than 11 TWh of heat only in Switzerland [9]. It was not possible to analyse all individual networks for their potential suitability for BILS. It is however striking that a considerable majority of the networks are based on biomass and waste heat. For these networks it can be assumed that they will suffer from shortage of biomass and waste heat. Seasonal storage solution will therefore be a key technology for many of these networks. The energetic potential is not a BILS specific question and therefore not further followed up in this project. The potential is the same as for all other big storages in a district heating system and this is very much depending on the size and the mode of operation of the whole system. BILS is adding another option where to place a storage. The energetic potential of big storages in Switzerland is analysed in the SFOE project BigStoreDH[2].

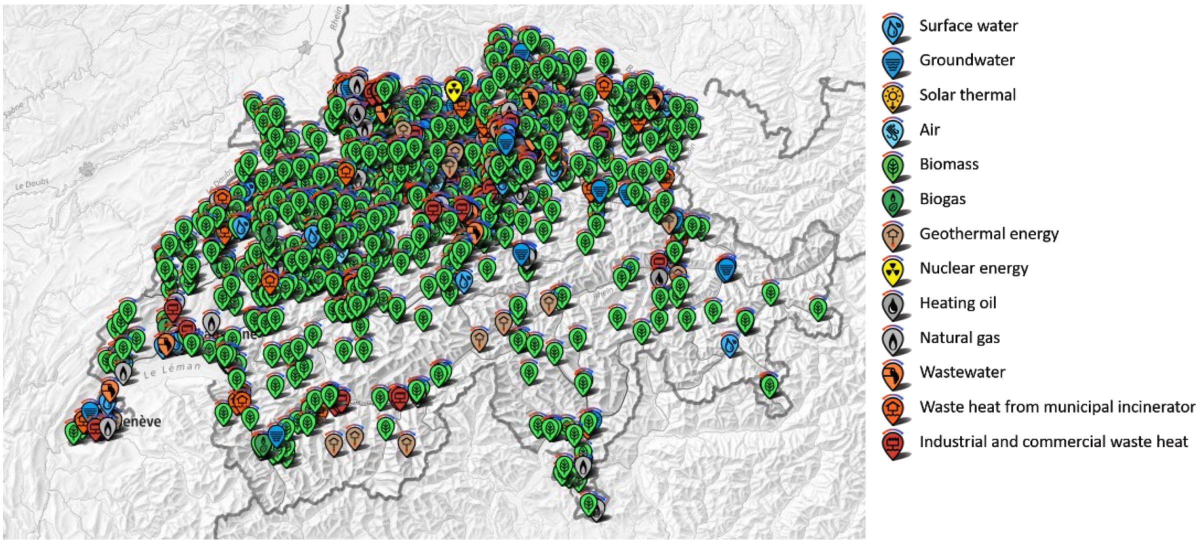


Figure 1: Map of the thermal networks in Switzerland[3] (district heating, local heating or district cooling)

It was also not possible to determine the distances of the thermal nets to a body of water where BILS could be located. A relation can be made between the number of habitants in the biggest cities in Switzerland and on the available lakes nearby these cities. The biggest cities in Switzerland which can

[2] https://www.ost.ch/de/projekt/bigstoredh-grosse-waermespeicher-fuer-waermenetze-1194

[3] https://s.geo.admin.ch/a2d614c2be

be considered as being nearby a lake are tabulated in Table 1 (data taken from Wikipedia on 03.03.2022). For the following estimation of the potential an indicative distance of less than about 10 km to the lake was considered as reasonable. In total it was found that more than 2 Mio persons live close to a standing water in Switzerland. Assuming a distance of up to 100 km as considered reasonable in earlier studies (see chapter 4.2) would change the picture again so that for Switzerland virtually every person is located close enough to a standing water to profit from a BILS. It can be doubted that this is a reasonable assumption. The potential is still good enough, especially for the bigger Swiss lakes such as the Lake of Geneva, the Lake of Zurich or the Lake of Lucerne.

#	City	Habitants	Near lake	Vol. (km³)
1	Zürich	421878	Lake Zurich	3.9
2	Genf	203856	Lac Léman	89
4	Lausanne	140202	Lac Léman	89
7	Luzern	82620	Lake Lucerne	11.9
9	Lugano	62315	Lago di Lugano	6.6
10	Biel/Bienne	55206	Lac de Bienne	1.2
11	Thun	43476	Lake Thun	6.5
16	La Chaux-de-Fonds	36915	Lac de Neuchâtel	14
18	Uster	35337	Greifensee	0.161
20	Vernier	34898	Lac Léman	89
21	Lancy	33989	Lac Léman	89
22	Neuenburg	33455	Lac de Neuchâtel	14
23	Emmen	31039	Lake Lucerne	11.9
24	Zug	30934	Lake Zug	3.2
25	Yverdon-les-Bains	29955	Lac de Neuchâtel	14
26	Dübendorf	29907	Lake Zurich	3.9
27	Kriens	28245	Lake Lucerne	11.9
29	Rapperswil-Jona	27483	Lake Zurich	3.9
30	Meyrin	26129	Lac Léman	89
31	Montreux	26090	Lac Léman	89
34	Wädenswil	24832	Lake Zurich	3.9
35	Baar	24686	Lake Zug	3.2
38	Horgen	23090	Lake Zurich	3.9
39	Carouge	22536	Lac Léman	89
40	Kreuzlingen	22390	Lake Constance	48
43	Nyon	21718	Lac Léman	89
48	Renens	20834	Lac Léman	89
51	Vevey	19752	Lac Léman	89
55	Onex	18933	Lac Léman	89
56	Volketswil	18865	Greifensee	0.161
58	Pully	18694	Lac Léman	89
62	Thalwil	18278	Lake Zurich	3.9
70	Val-de-Ruz	17143	Lac de Neuchâtel	14
71	Cham	17042	Lake Zug	3.2
77	Freienbach	16520	Lake Zurich	3.9
79	Morges	16101	Lac Léman	89
80	Steffisburg	15991	Lake Thun	6.5
82	Lyss	15763	Lac de Bienne	1.2
83	Locarno	15728	Lago Maggiore	37

Continued				
#	City	Habitants	Near lake	Vol. (km³)
83	Locarno	15728	Lago Maggiore	37
87	Arbon	14950	Lake Constance	48
88	Mendrisio	14902	Lago di Lugano	6.6
89	Küsnacht	14811	Lake Zurich	3.9
90	Stäfa	14791	Lake Zurich	3.9
92	Thônex	14573	Lac Léman	89
93	Meilen	14539	Lake Zurich	3.9
95	Horw	14211	Lake Lucerne	11.9
96	Amriswil	14211	Lake Constance	48
97	Ebikon	14066	Lake Lucerne	11.9
98	Richterswil	13670	Lake Zurich	3.9
100	Küssnacht (SZ)	13531	Lake Lucerne	11.9
101	Zollikon	13311	Lake Zurich	3.9
103	Versoix	13281	Lac Léman	89
104	Gland	13258	Lac Léman	89
107	Ecublens	13157	Lac Léman	89
110	Spiez	12926	Lake Thun	6.5
112	Chêne-Bougeries	12621	Lac Léman	89
115	Rüti	12494	Lake Zurich	3.9
116	Le Grand-Saconnex	12378	Lac Léman	89
117	Prilly	12360	Lac Léman	89
120	Arth	12184	Lake Lucerne	11.9
121	Pfäffikon	12174	Pfäffikersee	0.058
124	La Tour-de-Peilz	12068	Lac Léman	89
128	Veyrier	11861	Lac Léman	89
133	Männedorf	11397	Lake Zurich	3.9
135	Romanshorn	11327	Lake Constance	48
136	Risch	11212	Lake Zug	3.2
141	Maur	10780	Greifensee	0.161
144	Plan-les-Ouates	10601	Lac Léman	89
145	Val-de-Travers	10579	Lac de Neuchâtel	14
146	Sarnen	10514	Sarnersee	0.244
149	Aigle	10462	Lac Léman	89
150	Lutry	10459	Lac Léman	89
152	Sursee	10361	Sempachersee	0.66
155	Gossau	10282	Pfäffikersee	0.058
156	Bernex	10258	Lac Léman	89
160	Steinhausen	10198	Lake Zug	3.2
161	Payerne	10069	Lac de Neuchâtel	14
	Total	2269380		

Table 1: List of the biggest cities in Switzerland located close to a lake (distance less than about 10 km), such that BILS could potentially be of interest. Indicated also the number of habitants (2022) and the volume of the applicable lake.

It is important also to understand that even very big BILS would not substantially inflict traffic. To illustrate the size, Figure 2 shows a map with a BILS of 100 m diameter place in the bay of Rapperswil (just to compare: The longest ferryboats and steamships on the lake of Zurich have a length of about 60 m). Furthermore, a BILS will not stand out of the water by more than maximum one meter. Such a 100 m storage would however already have the double volume of the world’s largest seasonal pit storage for solar heat in Vojens Denmark.

For the planning and building of BILS it is essential to know the local currents and temperatures. These can be found in excellent quality from the eawag (Swiss Federal Institute of Aquatic Science and Technology) under www.alplakes.eawag.ch for some of the most relevant lakes where BILS could be used. It can be assumed that also other lakes could be described in the same way and using the same tools. For this project it is therefore assumed that currents and temperatures of lakes are known.

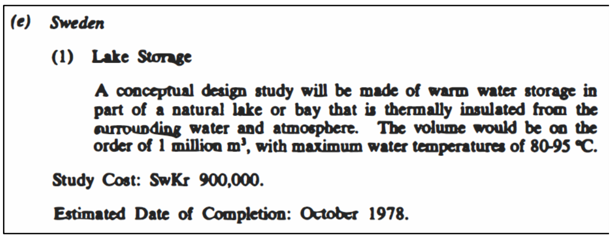
Figure 2: A BILS with a diameter of 100 m placed in the bay of Rapperswil to illustrate the size of such storages when located in a lake.

4.2 Literature studies

No recent literature was found dealing with the general idea of placing big thermal storages in lakes and standing waters. The idea was however already discussed in 1978. Documents of the International Energy Agency (IEA) on an implementing agreement for a *programme of research and development on energy conservation through energy storage* [10] can be found where budget was allocated for a conceptual study in Sweden for lake storages in the range of up to 1 Mio m^3. The idea was discussed further and was also presented in a conference in 1981 [11] and then again in a study made for the U.S. Department of Energy in 1984 [12]. The idea is discussed under the name Lake STES and obviously at that time no tangible results from the Sweden project were available. It can therefore be assumed that this project in Sweden was not carried out for unknown reasons, or maybe due to the small available budget.

The authors of this last study concluded that "*Lake STES promises very low costs and very large capacities. Lakes have the advantage of not requiring excavation, and construction with modular assemblies can be rapid and simple. Despite this concept's attractiveness, lake storage research has been limited to scoping studies, and no sizable development has commenced. Development of an insulation system that will not absorb moisture is very important to maintain good thermal effectiveness.*

Sites for lake storage are likely to be limited for environmental reasons and by regulatory and alternative-use priorities. Sites at or near power plants, and where the distance to a large consumer is less than 100 km should be investigated. Power plants are good thermal energy sources, and their waste heat needs to be marketed. Future plants would have increased justification if they were operated as both electric and thermal generation (cogeneration) facilities."



(e) Sweden

(1) Lake Storage

A conceptual design study will be made of warm water storage in part of a natural lake or bay that is thermally insulated from the surrounding water and atmosphere. The volume would be on the order of 1 million m³, with maximum water temperatures of 80-95 °C.

Study Cost: SwKr 900,000.

Estimated Date of Completion: October 1978.

Figure 3: Excerpt from the document [10] on an IEA program where one work package is dealing with a similar concept

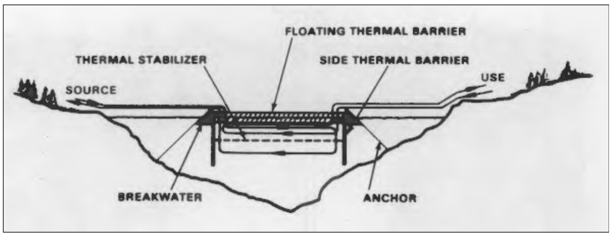


Figure 4: Sketch of the approach presented in 1984 [12]

No information or more publications could be found on this topic after 1984. It simply seems that there was no more work done on these concepts and that there is no real experience and no scientific work available dealing with this approach.

4.3 The BILS concept

The core idea of the BILS approach is the use of flexible envelopes in a lake (or any other standing water). By using flexible materials, the static behaviour of the reservoir is expected to be relatively simple, as only a portion of the standing water is separated and then used as a thermal storage. The forces induced by underwater currents, waves or pressure changes due to thermal differences, are expected to deform the flexible envelope only. A rigid envelope would need to be strong enough to cope with these forces. Furthermore, any stiff envelope would be heavy and much more challenging to install. As everything is flexible, no extensive underwater construction work should be required: The construction of such a storage tank should essentially consist of placing the envelope in the water, fill with water and to anchor the device on the ground to avoid drifting away.

Consequently, all approaches based on rigid devices and devices built at the bottom of a water body are not considered in this project. These approaches are also interesting and are considered in other projects such as for example in the StEnSea project[4] where spheres made of concrete are used a pressure stores. Similar devices could also be seen as underwater heat storage units.

Basically, a BILS can be thought of as an open or a closed device. The version proposed in 1984 was designed as an open container. Side walls and top were closed and insulated; the bottom was thought to be open. The main advantage of such a design is of course that installation and operation is probably quite simple. As far as pressure or buoyancy issues are concerned, there is no advantage to leaving the bottom open compared to when using a flexible bottom. Of course, the main disadvantage of that concept is the thermal exchange with the lake though. It seems, that sufficient stratification was expected so that thermal losses on the bottom can be ignored. However, the experiments made in this project show, that such a static stratification cannot be assumed in natural waters (see chapter 4.8.8) as there are always water currents and waves that would lead to high thermal losses. Furthermore, an open storage would most probably also lead to ecological problems as there would be zones of rather warm water at the transition between storage and lake. Such zones could be an interesting habitat for some invasive

[4] www.iee.fraunhofer.de/en/topics/stensea.html

species that should not be supported [13]. As no clear advantages could be identified in favour of open structures, it was decided to only investigate further the option of closed BILS.

The two main concepts that are further investigated are the submerged BILS (Figure 5) and the surface BILS (Figure 6).

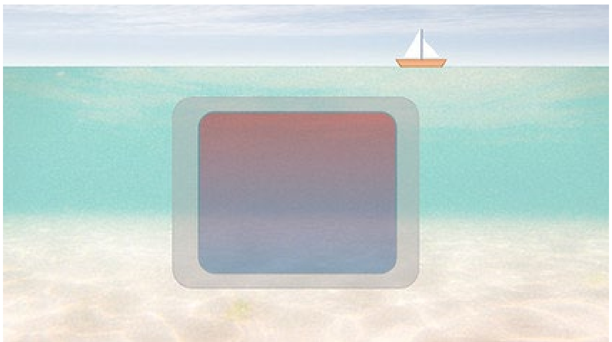


Figure 5: Schematic view of a submerged BILS.

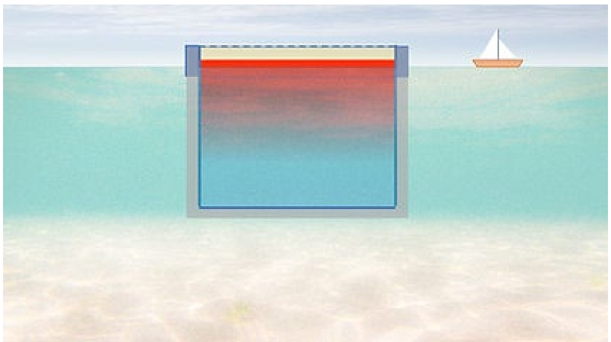


Figure 6: Schematic view of a surface BILS.

Essentially there are many advantages of submerged BILS such as that they are not visible and that they are not hampering traffic and leisure activities on the lake, if submerged sufficiently deep. Technically speaking the main advantage would be the stable and plannable conditions under water (www.alplakes.eawag.ch) as well as the protection from weather and UV impacts. On the other side the accessibility for maintenance and for the connection to a thermal grid would probably be more complex than for a surface BILS. The advantages of the submerged BILS are basically the disadvantages of a surface BILS. Visibility and obstruction of traffic, exposure to weather and UV versus ease of access.

Both approaches are further investigated, and additional pros and cons were identified in the course of this project.

4.4 Buoyancy

One of the major factors that must be mastered is - as simple as it sounds - buoyancy. Considering the hot water content of the storage tank, it is obvious that this tank is subject to buoyancy forces that drive the tank to the surface (Archimedes' law). Assuming that the envelope and insulation are chosen to have a similar density to water, a heated cylinder of water will rise to the surface and should partially protrude from the surrounding water. In Figure 7 the relation between temperature and visible protrusion is illustrated for a water cylinder of 20 m diameter/height. A protruding height of maximum 0.8 m must be expected for a storage at 100 °C in a lake at 20 °C. The expected forces could be handled by using for example steel ropes or other reinforcing elements. However, the experiments (See chapter 4.8.1 and Figure 22, Figure 23) will show that this is not resembling the real behaviour of the BILS.

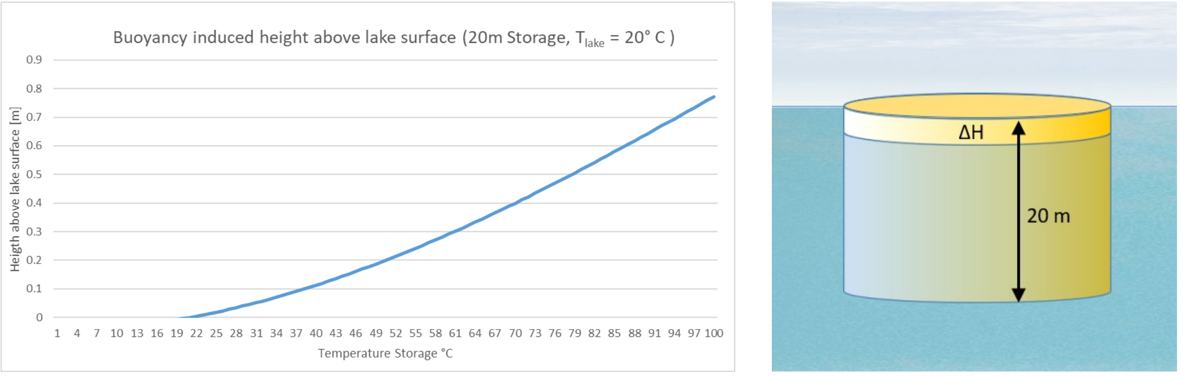


Figure 7: Buoyancy induced uplifting of the BILS.

For submerged BILS, it would be necessary to increase the density of the storage tank so that it is higher than that of the surrounding water. This can be achieved by using weights attached to the BILS or by suitably mooring the BILS to the ground. The required forces on the BILS envelope would however be very high and most probably would require very robust envelopes. This option was not yet further investigated and will be part of a follow up project (see chapter 7 of this report)

Another possible solution was investigated, namely the use of salt water as a storage medium. The density of salt water is slightly higher than that of lake water. Figure 8 shows the relation between required NaCl content and the temperature to reach a point where the BILS would sink and consequently disappear form the lake surface (submerged BILS).

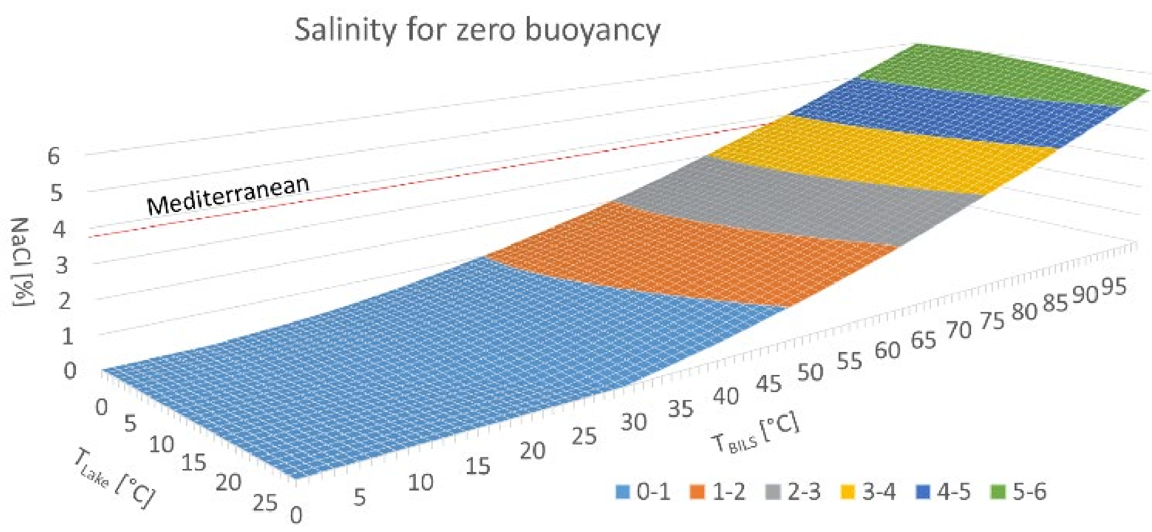


Figure 8: Relation between required salinity for zero buoyancy at different temperatures of the lake and the BILS

The required salinity is of course depending on the temperature of the lake and the storage. However, the calculation shows that a salinity of about 6 % would be sufficient to hide a hot BILS at 100 °C in a cold lake. Just for comparison: The Mediterranean Sea has a salinity of almost 4 %. This behaviour was also investigated in the experiments we carried out in this project (see chapter 4.8.3). These experiences have shown that this could in principle be a suitable option and that it is possible to hide a hot BILS even in cold water. This solution has however also some drawbacks, where the amount of required salt is only one factor. The environmental risk in the event of a BILS burst and the associated sudden release of salt water into a lake would probably be acceptable, considering how much salt is dumped in waters during harsh winters[5]. The main caveat for this salinity solution is however the seasonal fluctuation of lake temperature and storage temperature. Salt can easily be added to a BILS but cannot be easily removed anymore. It could be a solution if the salt content is controlled very precisely to a certain temperature range and the BILS is used only in a narrow band of operating temperatures. Depending on the intended mode of operation, this could still be an option. But for the general applications there must be a technical solution to control buoyancy.

Other technologies such as submarines or balloons have a similar behaviour to a submerged BILS: The floating height above the seabed (submarines) or above ground (balloons) is determined by buoyancy. From these devices it is known that a free-floating position is always an unstable position, either ascending or descending. To maintain a certain height above ground, considerable effort is always required, e.g., motors, propellers, dropping ballast, heating up the contents, air pumps, controllers, mooring, etc. With surface swimming devices such as ships, which are also dependent on buoyancy, the controlling is much easier and the simple Archimedes' law applies: As long as it is floating at the surface, the ship is in a stable position.

Given the expected buoyancy behaviour, it therefore seems very difficult to keep a BILS completely underwater without further technical measures, unless only a very small temperature range is being used. There are several options that could be investigated further to submerge any BILS. The most straightforward solution is for sure anchoring the device to the ground of the lake. The main problem here is that the envelope needs to be reinforced considerably, for sure the fixing points where the anchoring forces must be adopted. However, this is somehow in contrast to the basic idea of having a flexible outer envelope. Still, in this way the uplifting forces could be handled. When the storage cools down, it will sink to the ground. This sinking must also be prevented to protect the storage from being damaged on the lake bottom. The most straightforward option would be the use of additional tanks that are filled with air when needed. Adding such tanks would also require further reinforcement of the whole storage. It is therefore considered possible to submerge a BILS using saline water, but the additional technical effort required is considerable. This is not in line with the intended general concept of a rather light and flexible storage facility. For these reasons and following the experimental work (See chapter 4.8.3), it was decided to focus on surface BILS in this project. Submerging the storage is not excluded but would have to be treated in another supplementary project.

4.5 Insulation material

As already mentioned in the report of 1984, the development of an insulation system that will not absorb moisture was considered as very important. Another major selection criteria are the environment impacts in case of a disastrous accident, hence when the insulation material is released in the lake. Even if the material is enclosed, it must also be expected that some amounts of water can contact the insulation material. The use of materials such as oils or persistent toxic substances is therefore practically impossible in such a flexible system. There is for sure also a risk of algae growth or for the development of other forms of life inside the insulation. Countermeasures must be developed depending on the material, if necessary. The insulation must be enclosed in all cases to avoid contact with the environment as much as possible, so that properties such as UV resistance are not considered as a relevant criterium

[5] https://www.eawag.ch/fileadmin/Domain1/Beratung/Beratung_Wissenstransfer/Publ_Praxis/Faktenblaetter/fb_Streusalz_Nov2011.pdf

for the insulation material. Of course, physical properties such as temperature resistance from 0-100 °C are relevant, but also pressure resistance, lifetime, mechanical stability, or deformability, are part of the selection criteria. Mainly as a result of the first experiments with a conventional insulation material (see chapter 4.8.2) it has become clear that any insulation material to be used for the BILS concept must have a density in the range of the surrounding and the enclosing water, to avoid strong uplifting or downward pulling forces on the entire envelope.

Conventional pit storages on land are built without side additional insulation. Basically, a watertight liner is placed directly in the pit and then the storage can be used. The side and bottom of the storage consist of normal soil. As the heat conductivity in dry soil is low, additional insulation is considered to be not required. After filling up and heating up the storage, it may take however 2-3 years until a thermal equilibrium in the surrounding ground is established, meaning that in this time the initial thermal losses are higher, as part of the heat is absorbed by the surrounding ground. One of the worst-case scenarios for a convention pit storage are groundwater flows around the storage. If so, a permanent heat flow from the storage into groundwater is cooling the storage continuously. In addition, in a stable container such as a pit storage system, internal convection is minimized, and stratification can be easily controlled by operating the storage system appropriately. This all leads to a very stable situation for a pit storage that is essential to minimize thermal losses.

The situation is completely different with the BILS concept. The surrounding medium is not a stable ground in which a stable temperature gradient can develop over a long period of time. The surrounding medium is flowing water with virtually unlimited heat capacity. This is basically the situation that occurred in our first experiments (see 4.8.1), where the heat losses made it practically impossible to heat up the storage tank. Furthermore, in a real size BILS also the inside of the storage is not standing water, but the content will be mixed continuously as a flexible envelope will be used. Waves and currents in the lake will be transferred to the inside of the BILS so that the content of the storage is permanently mixed and natural stratification is not to be expected.

One of the main challenges is therefore the thermal insulation of the storage. To find a good insulation material, four physical mechanisms must be considered:

- Heat conduction through mechanical contact
- Convection, the transport of thermal energy in a flowing medium,
- Thermal radiation
- Losses through evaporation

The specific challenge for BILS is to find a material that has suitable properties under water, and thus also under pressure. All materials in which the thermal conductivity is mainly determined by the content of air or air bubbles are therefore a priori excluded. These materials cannot be considered resistant to pressure and prolonged exposure to moisture. To tackle this topic a critical review of potential materials was conducted. The basis for this study is a comprehensive collection of data for the thermal conductivity (λ) and density (ρ) for many materials that potentially are used as building materials. These data were analysed to identify possible candidates for BILS insulation.

For a flexible envelope, the insulation material must be flexible as well. The BILS idea is based on a thin and flexible skin that is not able to absorb high forces. Furthermore, and basically for the same reason, a very relevant parameter is the density of the material. If the density differs too much from water (inside and outside) the insulation will induce high up- or down-lifting forces on the envelope. Of course, ecological and at some point, also economical aspects must be considered as well.

Figure 9 and Figure 10 show the relation between thermal conductivity and density of all the building materials listed in [14]. There the materials are grouped into the four categories impermeable, non-hygroscopic, inorganic-porous, organic hygroscopic which are relevant for construction products.

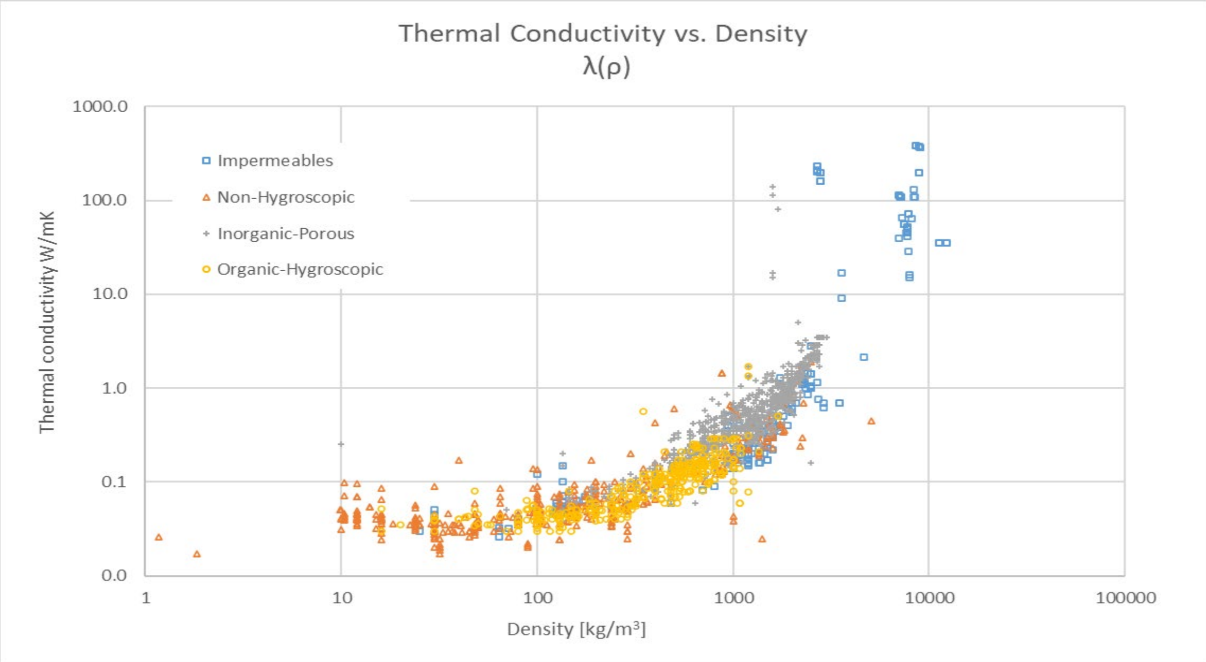


Figure 9: Relation between thermal conductivity and density of building materials [14].

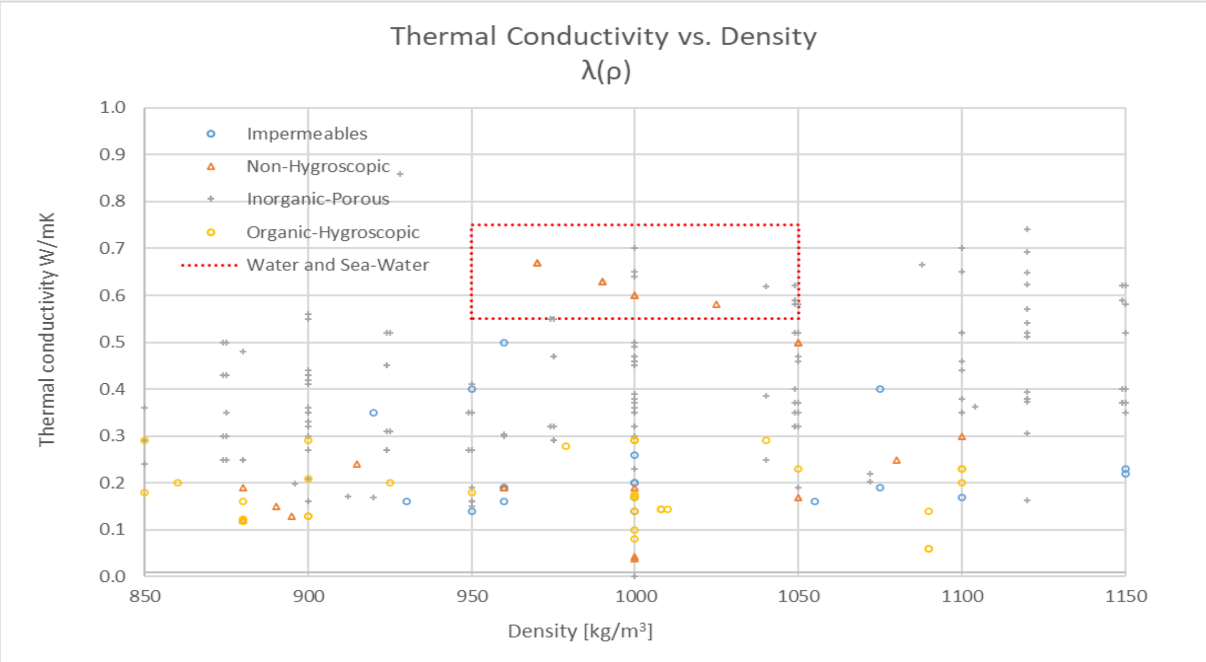


Figure 10: Close look at the materials where density is in the range of 950-1050 kg/m^3.

Inorganic hygroscopic substances such as Silica Gel, Calcium Chloride, Sodium Hydroxide (Caustic Soda), Potassium Hydroxide, Sulfuric Acid or Aluminium Chloride are not listed in this database. These materials are generally not used as building materials, but rather as "moisture regulators" or desiccants materials.

A striking insight is that obviously all these hundreds of materials are located rather close together on a bended curve with only limited scattering (Figure 9).

Looking at the materials plotted in Figure 10 (taken from [14]) there are some materials with the desired density of about 1000 kg/m^3 but with rather low thermal conductivities. As these materials would be the most preferred materials these were investigated further. However, these datapoints turn out to be either erroneous or unsuitable for our application. The material listed with the lowest thermal conductivity is *resin bonded mineral wool* with λ = 0.04 W/mK, hence conventional mineral wool. In this case obviously, the density was measured in compressed form, where the thermal conductivity would be much higher, especially when the material is wet. A similar data point is *woven wool*, where again the thermal conductivity is much higher when wetted and the density must have been measured in compressed from as well. The other listed materials are leather (λ ≈ 0.14 W/mK), wooden hardboards (λ ≈ 0.2 W/mK) and other materials such as resin, linoleum or rubbers (λ ≈ 0.15-0.20 W/mK). The most promising material in this class would be natural and synthetic rubbers where the density can be partially designed to match the requirements, and which can reach thermal conductivity in dry form down to λ ≈ 0.15 W/mK. Especially some silicone rubber materials could be of interest also due to their thermal and chemical stability and their salt impermeability.

In a similar range are found several bituminous materials. For environmental reasons, these materials are not considered particularly suitable for use in lakes. Another interesting class of materials are the various greases and lubricants with λ ≈ 0.13 - 0.20 W/mK. The density is slightly too low but could most probably be adjusted chemically. Also here, these materials are not particularly suitable for use in lakes due to environmental concerns. However, if necessary, it seems possible to contain these substances to such an extent that they could probably still be used.

Other materials such as polyethylene in various versions (λ = 0.3 - 0.5 W/mK), or polystyrene could be used as insulation material, whereby the long-term temperature stability up to 100 °C must be doubted (or is associated with a high costs) and in addition the thermal conductivity is nevertheless not less than 0.3 W/mK.

Other inorganic materials such as expanded clay, concrete (that can be designed for any density), gypsum boards, masonry, plaster, vermiculite, and similar have a thermal conductivity λ > 0.3 W/mK. The density is however usually adjusted by adding air bubbles. It is hence questionable whether this density would remain stable in a wet environment such as a lake. Also, for Pumice the density is depending on air bubbles. Other materials such as asbestos containing materials are not considered for obvious reasons. All these inorganic materials are furthermore stiff and would preferably be more of interest for a static building (for example a storage built on the ground of a water). In the BILS approach using flexible skins it seems to be natural to use also flexible materials for the insulation.

Organic materials such as wood, paper, leather, cork and wool, some of which have good thermal conductivities, are not considered because of their expected limited lifetime and/or because the λ is dependent on trapped air bubbles.

Oil-based liquids (natural and synthetic) have a density slightly below 1000 kg/m^3 and a λ-value in the range down to 0.1 W/mK. However, this class of material must probably also be excluded for use in lakes for environmental reasons. On the other hand, there are also some animals (whales, elephant seals, etc.) that survive in icy waters and whose thermal insulation consists of fat (i.e., solidified oils). Obviously, also the density can be adjusted accordingly. This option has not been investigated further for the time being, although it could potentially offer interesting solutions for BILS.

Other liquids such as aniline, cresol, benzaldehyde, N-methylpyrrolidone, isopropylbenzene hydroperoxide, acetic acid and many more can be found with some advantages and a density in the range of water and a relatively low thermal conductivity. However, for all these substances some serious disadvantages have been identified, such as high reactivity, cost, environmental impact, lack of temperature stability, etc. so that they are not further considered.

In summary the materials with the best properties are rubber types, bituminous materials, members of the polyethylene family, and lubricants. All these materials have a thermal conductivity in the range of λ > 0.15 W/mK, appropriate density and seem to be affordable and manageable with the necessary efforts.

One material that has not yet been discussed as an insulating material is water. The thermal conductivity of water is in the range of λ = 0.5 - 0.68 W/mK (Figure 11). This is higher than some of the materials discussed before. On the other hand, the materials discuss before are only partly satisfactory for several reasons. In particular, there is no material with an extremely low thermal conductivity well below 0.1 W/mK that would justify the effort required for the use as BILS materials.

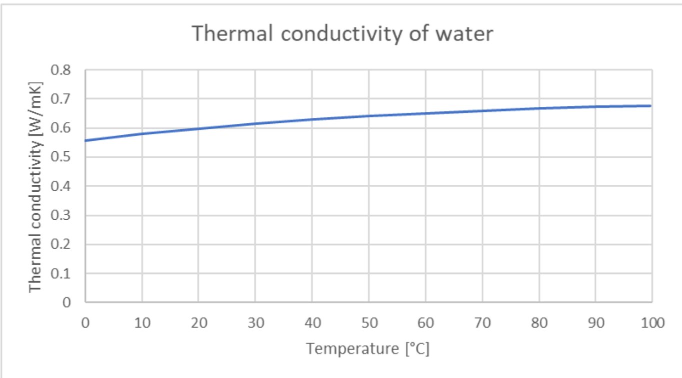


Figure 11: Thermal conductivity of water.

The effective heat loss of a material is determined by its U-value, essentially by the product of the thermal conductivity and the insulation thickness of the insulation. If we compare water as an insulating material with, for example, conventional rock wool (λ = 0.03 W/mK), this simply means that the insulation thickness must be 20 times greater when using water than when using dry rock wool. Considering that a typical BILS will have a diameter of at least 20 m, it does not seem to be a problem to add 2-3 m of diameter because of the additional insulation material. The main advantage of water is obvious: the material is environmentally neutral and even in the worst-case scenario of a complete loss of the material in the lake, there is no ecological disaster to be feared.

The use of water seems to solve many problems as the density is naturally similar to the surrounding lake and the reservoir contents. There are no environmental problems to worry about and the material is available free of charge on site and easy to dispose of if necessary.

When using liquids as insulating material, not only the thermal conductivity but also the losses through convection must be minimized. Water is not really known as a good insulating material, mainly because it is a liquid and therefore allows a high level of energy transport through convection. The thermal conductivity of water is $\lambda \approx 0.6$ W/mK only under the assumption that water is immobilized.

Several options were considered to immobilize water. Figure 12 shows three types of materials that were considered as potentially useful to immobilize water by mechanical means. One option could be to implement a honeycomb type structure (Figure 12, left) over the whole insulation thickness. Depending on the size and orientation of the honeycomb cells, it should be possible to reduce water currents and reduce convection. Honeycomb structures are widely used in packing industry and therefore should be producible. It is however questionable whether flexible but still strong enough structures with the required temperature stability can be supplied at reasonable costs. A second material that was investigated and which seems to be promising is a polyurethane (PU) foam that is widely used in water filtering applications (Figure 12, centre).

These filter foams are made as pore-controlled polyurethane foams with a precisely defined, regular pore size. The number of pores is defined in PPI (pores per inch-linear). Several relevant properties are making the material interesting for the application in BILS. The material is stable up to a temperature of 140 °C, even when used for long periods of time. The material has its own structure yet is still soft and flexible. It would therefore also give a BILS a certain external structure when used as an insulating material. The material is used, for example, as filter mat in aquariums and in various industries and can be considered chemically harmless. The biggest disadvantage is the cost of the material, which is in the range of 1000 – 2000 CHF/m^3. Another disadvantage is that these filter foams have a completely open pore structure with a very low pressure drop, as they are used in filters. This means however also that convection is not strongly suppressed. For sure it would be possible to design this material for higher flow resistance, however currently it does not seem to be available with this property. Furthermore, the available material does not seem to be producible in thicknesses of much more than 10 cm, which means that setting up a 2 – 3 m thick insulation for a BILS would also require about 20 - 30 layers, so would also require a lot of engineering and fixing work. This would be feasible, and the material is still considered as a potential material to be used in future BILS.

The last material that was investigated is a conventional insulation (Figure 12, right) that is also used for conventional thermal storages. These are also flexible polyurethane foams, however with much smaller air bubbles and with a distinctly different structure.

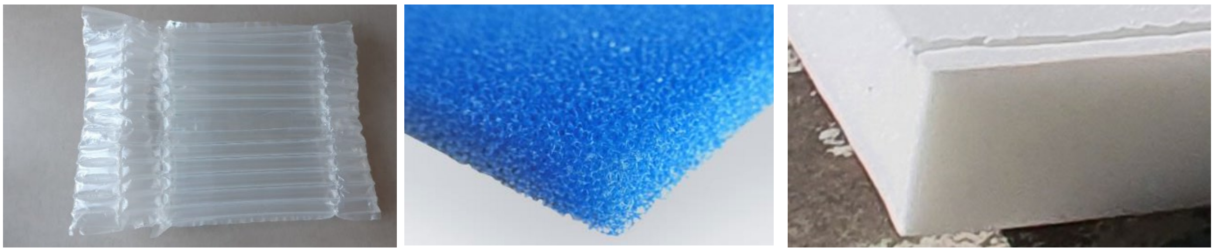


Figure 12: Different approaches for immobilizing water by technical means.
Left: Honeycomb type packing material
Centre: Open cell polyurethane filter foam
Right: Conventional polyurethane insulation for domestic hot water storages

No experiments were made with the honeycomb materials. The principle of using honeycomb to reduce convection is used for example in a specific high performance solar thermal collector product[6]. There the plastic honeycomb is added on the inside of the front glass of the collector to reduce top losses on the front side by reducing convection (See Figure 13).

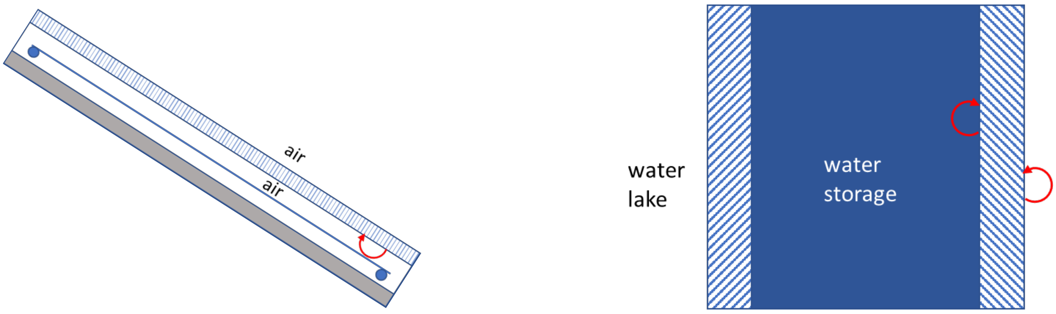


Figure 13: On the left side schematic of honeycomb material used in solar collectors. Direction of honeycombs is more or less vertical. Convection is reduced (thermosiphon effect).
On the right side, the possible use on a BILS storage. Horizontal to vertical direction of honeycomb was considered.

If this concept is to be used under water for a BILS, the thickness of the whole honeycomb layer must be much higher, and/or the density of the honeycombs must be much higher. This is because the medium water has a much higher thermal capacity and therefore much more energy is transported than with air. The direction of the honeycomb structure could be vertical, horizontal or under a certain angle. With all these concepts, there is the main problem that there is no experience with closely meshed flexible honeycombs and we did not find a supplier for such materials. Trials to produce such structures in house, showed that this is not feasible in the frame of this project as new production technologies would have to be developed first. Furthermore, the experiments with the open cell PU filter foam (chapter 4.8.5) confirmed later that the convection is not suppressed sufficiently if the fluid can flow inside the structure. For these reasons the honeycomb approach was not further investigated, but with the other two materials, additional experimental investigations were made as described in chapter 4.8.5 of this report.

An alternative approach to immobilize water could be the use of some kind of binding agents that are used in various industries and for various applications. This could be for example Silica gel or other inorganic hygroscopic substances. Silica gel can absorb about 40% of its own weight in water and fully saturated Silica gel could be considered immobilized water with a reasonable density. However, one class of materials that has even more attracted our interest are the so-called super-absorbents (SAPs).

Super-absorbents are materials that can absorb extreme amounts of water. The potential of this material is to absorb 200 to 1000 times its own weight in water. The material is produced as a white, coarse-grained powder and is used in various applications. In chemical terms, super-absorbents are copolymers of acrylic acid and sodium acrylate, where the ratio of the two monomers can be varied to engineer the properties of the material to some extent. When added a water-based liquid, this is absorbed by the superabsorber and the superabsorber particles swell up strongly and produce a so-called hydrogel. This

[6] https://www.tigisolar.com/#technology

class of materials appeared only in the late 1970s and has become since then useful in many applications such as

- Cable sheathing for power and communication cables (to prevent moisture build-up)
- Packaging industry for moisture-sensitive foodstuffs and liquid-releasing goods.
- Food and flower transport in cold or even frozen bags (see also chapter 4.8.7)
- In agriculture and for indoor plants as a water and nutrient reservoir.
- Fire protection
- In cosmetics and medicine
- …

Many more applications are known, and new applications are further developed. The material that we used at the beginning to demonstrate its behaviour is usually sold as “magic snow powder” and is distributed as children's toys or is also used in film industry to simulate snow (Figure 14 and Figure 15).

Figure 14: A small amount of dry Superabsorbent powder before adding water.

Figure 15: The glass is just filled with water. After a few minutes all the water is absorbed, the glass can even be turned upside down.

The most prominent application is the use in diapers where not only the liquid absorption is relevant but also the fact that the liquid is virtually not released anymore, even under pressure. The cost for super-absorbents is basically low if not used for medical applications, and only small quantities are needed. For industrial applications, prices down to only 1000 USD/ton were found. Assuming an absorption capacity of 200-1000 times its own weight, this means that 200’000-1’000’000 litres of water could be immobilized for only 1000 USD.

As a result of these considerations and also following the experiments described in chapter 4.8.5, we consider the use of super-absorbents as the best option to immobilize water to be used as insulating material for BILS. One option that was not yet investigated could be the combined use of super-absorbents to immobilize water and some open cell PU foam to provide a flexible structure with some stiffness.

4.6 Top/Bottom insulation

The requirements for the top and bottom insulation of a BILS are depending strongly on the type of BILS. For totally submerged BILS the same insulation materials as for the side insulation can be used. For floating BILS, the top insulation must be designed accordingly. Here it is reasonable to understand the concepts that are currently used for conventional pit storages.

For conventional pit storages different layers with insulating materials are used to cover the surface, Figure 16 and Figure 17 show the surface of the pit storage in Høje Tåstrup (Denmark). These surfaces are walkable and thermal losses are sufficiently low. For sure, such a top lid is also required for safety reasons as the storage is filled with hot water. The cover lid is not only relevant to reduce thermal losses through convention, but also to reduce thermal losses through evaporation (one of the main sources of thermal losses also for swimming pools). However, one of the main problems encountered for conventional pit storages is the accumulation of rain/snow on the top of the storage. This water must be removed and should not enter the storage to avoid cooling effects. To manage rainwater, the surface is covered with pebbles and is segmented into several squares (visible in Figure 17), which are slightly funnel-shaped. In the centre of each of these funnels the rainwater is collected and pumped actively out of the field.

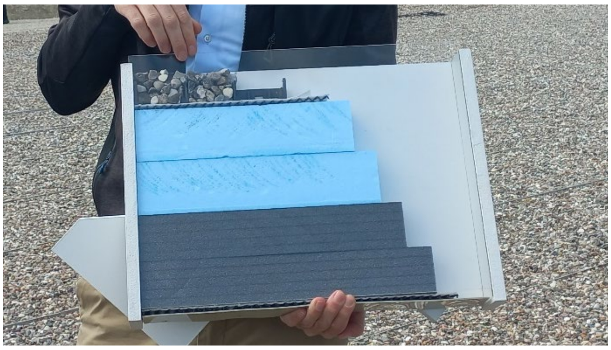


Figure 16: Cross section of the lid of the pit storage in Høje Tåstrup (DK)

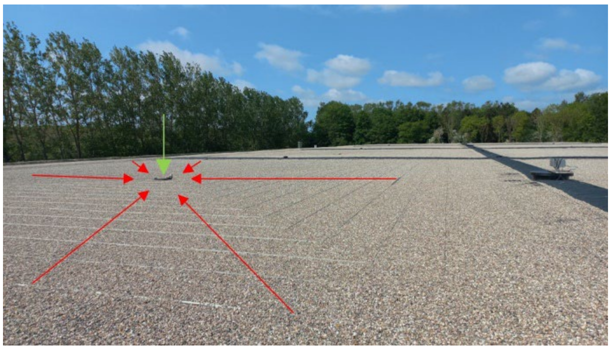


Figure 17: Surface of Høje Tåstrup (DK). Rainwater is directed to the centre (red arrows) where it is collected (green arrow) and pumped out of the field (not visible)

The cover (Figure 16) is basically made of several layers of insulation materials. On the bottom there is a thin impermeable liner to close the storage that is below the dark insulation material. The same liner is used on top (above the blue material) to avoid ingress of rainwater into the insulation and to guide the water to the centre of the mentioned squares (Figure 17). On top the pebbles to fix all and to reduce exposure of the in insulating materials to UV. By proper distributing the density of pebbles over the entire surface the funnel-shape of the surface is maintained only by the weight of the pebbles.

For surface floating BILS the questions and problems to be solved can be considered as very similar to those for conventional pit storages. Experience and expertise are available in specialized companies, particularly in Denmark. The main difference would be that probably more water is accumulating on the surface due to the waves, and that the whole external structure is not as rigid as for a land-based pit storage. It is not very likely that pebbles will be used for BILS, but most probably an active water removal system using pumps is required as well.

In the frame of this project the question on how to design the top lid of a BILS is therefore not further investigated. For surface BILS It can be assumed that similar technologies will be used as for land-based pit storages, for submersed BILS the top insulation would be similar to the side insulation.

4.7 Environmental impact on the lake

One of the frequently asked questions is of course the potential environmental impact of a BILS on the lake. Although this is not a major topic of the project, this must be considered of course.

On one side all the material that are selected or are planned to be used should not induce any harm to the environment. Some materials have been excluded for this reason.

Of course, all large structures in a lake have ecological effects (shading, local changes in currents, aquatic vegetation, etc.). On the other hand, the lake can also be expected to have an impact on the BILS, for example through algae growth on the surface or through colonization with Quagga mussels. These are however not specific BILS problems, but problems that apply to all construction work in a lake. They are therefore not be investigated further but are a topic in the follow-up project (see chapter 7).

One question that is BILS specific and that can be answered, is the thermal impact on the lake: Every thermal storage has losses and BILS will therefore potentially heat up their hosting lake. Of course, this is depending on several parameters such as the operating temperature of the storage, the size of the BILS and the lake and the insulation, etc.

Considering the case of the lake of Zurich: Assuming a cylindrical BILS with 40 m diameter and 40 m height (approx. 50 Mio litre capacity), normal insulation, storage temperature over the entire year close to the boiling point and a lake temperature constant at 4 °C. For such a BILS, the annual energy losses will be in the range of <2 GWh/y. On the other side, the energy scenarios of the city of Zurich estimate that in 2050 about 2-4% of the total heat demand will be provided by the lake [15]. This is about 30-60 GWh/y energy that is extracted from the lake. Apparently, the total energetic potential of the lake is estimated from 5000 GWh/y to more than 10'000 GWh/y, without having a significant biological impact on the lake.

Comparing the 2 GWh/y losses of the BILS (“heating up the lake”) with the 30 - 60 GWh/y that will be extracted anyway (“cooling down the lake”) shows that even very large BILS, will not affect the lake temperature in a noticeable way. Even an extremely large BILS with 500 Mio litre volume at the boiling temperature will provide only about 9 GWh/y loss, meaning that the problem of heating up the lake is virtually not relevant.

4.8 The experiments

4.8.1 General behaviour

The aim of the first series of experiments was to gain a general and basic understanding of how a flexible storage tank behaves in standing water, how such a device can be handled and to assess the heat losses of a non-insulated storage tank in water.

For this first series of experiments, a cylindric storage of 2 m height and 1.2 m diameter was built using PVC foils. The calculated volume is in the range of 2.26 m^3. Figure 18 shows the first BILS prototype inflated with air. Basically, it was designed as cylinder but obviously a cylinder cannot be expected to stay in cylindrical shape if flexible materials are used. To make the prototype usable for experiments, it was fitted with several openings, fastening elements and windows as can be seen in the pictures below.

The department of school and sport of the city of Zurich supported the project by allowing the project team, to use for some limited time the public swimming area “Zwischen den Hölzern” in Oberengstringen close to Zurich before the summer season started. This swimming area is not emptied during wintertime, but the water is exchanged in spring before the new season starts. The first series of experiments took place in March 2022. Indeed, this permittance can be considered as very valuable contribution to the project as the laboratory conditions are much better in such a controlled environment than in a real lake.

The goal of the very first experiment was to place the prototype in water, to fill it with water and to heat up as much as possible. In best case also to measure the temperature losses.

Figure 18: The first BILS prototype in the production atelier of Luft & Laune.

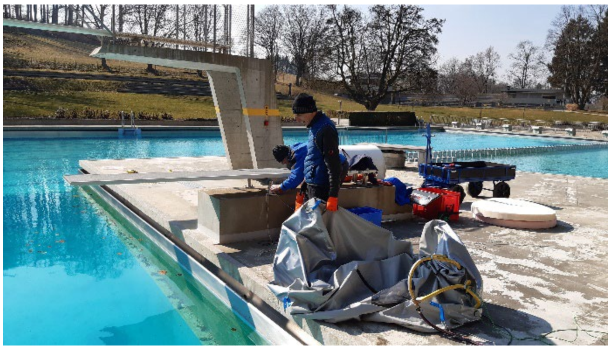


Figure 19: The prototype is brought to water.

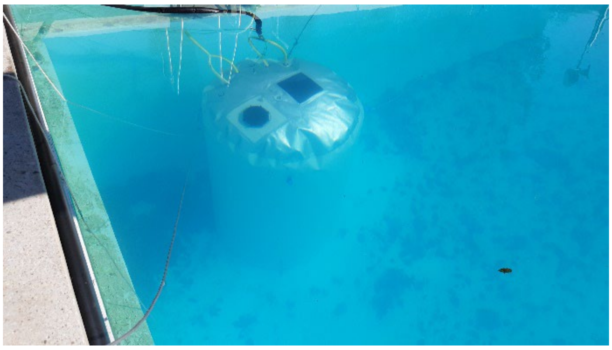


Figure 20: The prototype is filled with water and sinks down to the ground. The total density including all the equipment and the envelope was higher than the surrounding water.

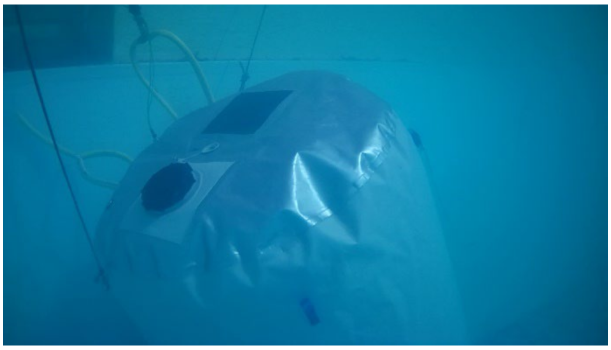


Figure 21: The prototype was provided with in- and outlets intended to heat up the content of the storage (yellow tubes on top). Some temperature sensors were placed inside the prototype.

Lesson learnt: What looks easy on the pictures is not easy in the real world. Even if we are talking about a rather small amount of water that is only separated by a thin and flexible skin from the surrounding water, it is still more than 2000 litres of liquid that must be fixed and must be moved. The BILS shows an unexpectedly high inertness, and the general handling requires good planning and mooring.

Lesson learnt: The shape of the BILS will change and will not remain cylindrical as outlined and planned. This is a relevant topic that must be considered when designing a bigger storage. The flexible skin has a behaviour similar to that of a balloon.

The prototype was heated up as high as possible using a transportable electric heater. As there was no insulation at all (except for the thin envelope), the maximum possible temperature was very limited, also because of the unfavourable ratio of surface to volume for this size.

As a result of this heating up process the prototype surfaced and tilted into a horizontal position. Surfacing was expected due to the heating-up. The tilting was not expected, instead we expected the storage to emerge from the water by a few centimetres, as outlined earlier (chapter 4.4).

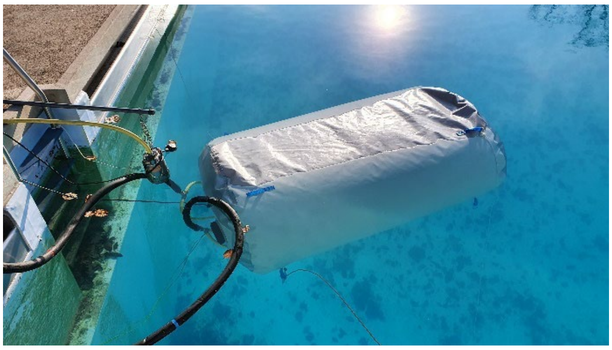


Figure 22: Buoyancy induced up-lifting of the BILS.

Figure 23: Flattening of the surface. The flexible body does not emerge from the surface

This tilting behaviour is of course explainable and is basically caused by the elongated shape of the prototype. To understand this floating behaviour, the body must be considered in a slightly tilted position (inclined position). Due to this inclination, the centre of gravity of the displaced water (Archimedes) is shifted with the buoyancy volume, while the centre of mass always remains unchanged. A wider body with a low centre of gravity will see a restoring moment, hence a stable floating position, while a narrower body with a relatively high centre of gravity would experience a tilting moment, hence an unstable floating position. The body is tilted and comes into a horizontal stable position.

The heating-up and temperature measurements are shown in Figure 24. For technical reasons, the maximum heating power was in the range of max. 11 kW. The maximum temperature difference that was possible with this setup was therefore in the range of about 12 K also due to the very high losses and the continuous mixing in the storage. The measurement follows the expected heating curve. As can be seen from the graph, the heating-up phase took several hours, indeed the storage was heated up unattended and it is not known when exactly the storage surfaced and came into the horizontal position.

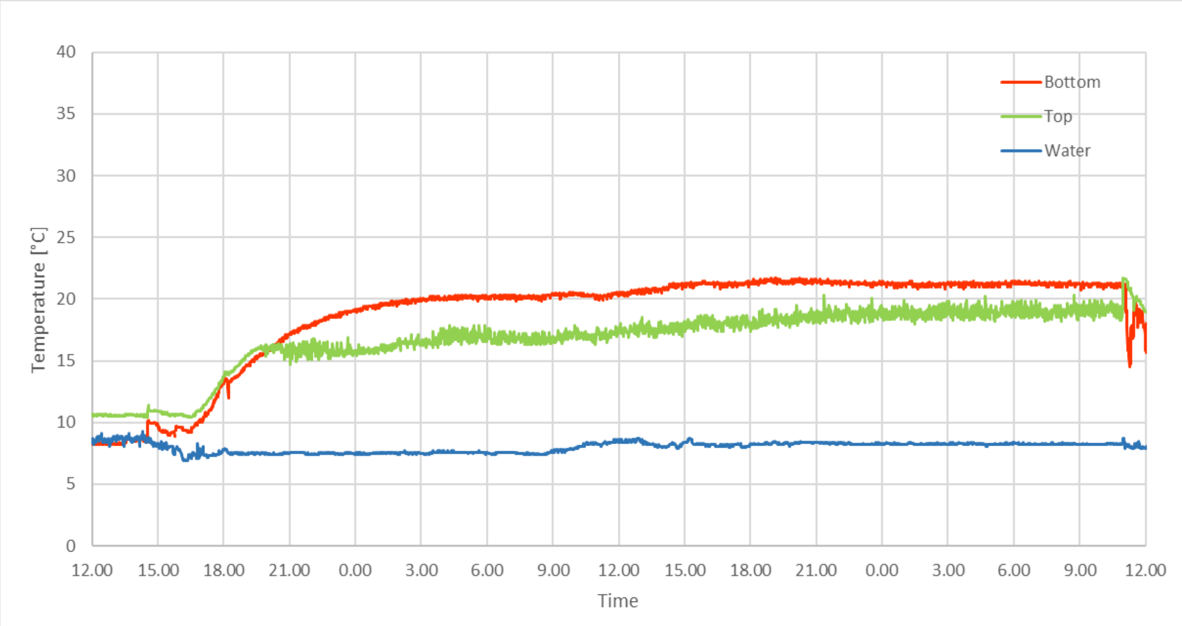


Figure 24: Heating-up of the first BILS prototype

Obviously at some point at about 20:00 the sensor placed at the upper end of the storage changed behaviour. It can be assumed that at this time the storage surfaced and came into it horizonal position, so that the sensor was moved closer to the envelope in a colder position.

The main outcome is that the diameter to length ratio is not only relevant to optimize the surface to volume ratio. It is also essential to keep the device in a stable swimming position and to avoid tilting forces. In general, the BILS is in a more stable position if the height is less than the diameter.

Furthermore, the BILS will not emerge from the surface when heated up. The assumptions and calculations made in chapter 4.4, are valid for rigid storages, but not for those with a flexible envelope. For a flexible device, the top of the storage will always be flat and be levelled to the surface of the lake. The weight of the part that is theoretically emerging (see chapter 4.3), will broaden the top of the BILS so as to become flat and even with the surface of the lake.

4.8.2 BILS with wetted conventional insulation material

The aim of this experiment was to understand and to verify whether a wet insulation works as expected, hence basically with the losses caused by the thermal conductivity of water but without convection losses.

For this experiment a conventional insulation made of a polyurethan foam (Figure 25 to Figure 28) was used, that was wrapped around the storage in a similar way as it is done in convention storages in buildings. To improve the effect, two layers were used each of 10 cm thickness. It was assumed that the entire insulating material would be wetted so that the behaviour of water as insulation material could be verified.

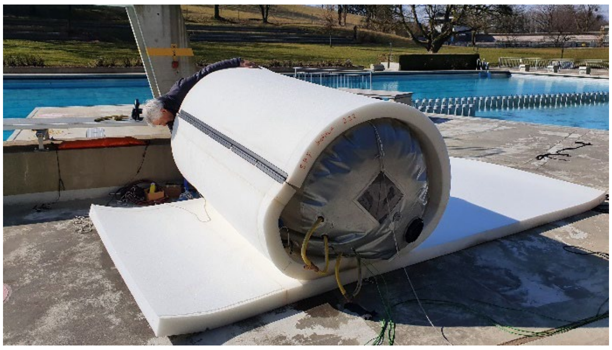


Figure 25: Prototype was furnished with two layers of conventional storage insulations.

Figure 26: The total thickness of the side insulation was 20 cm (two layers of 10 cm)

Figure 27: The bottom of the prototype was also covered with the same material.

Figure 28: Standing prototype. The top was left open to have access to the storage. It was not planned to sink the storage.

The intention of the experiment was to bring the BILS first in an upright position in water, with a totally wetted insulation, hence immobilized water. Then to heat up the storage to compare with the behaviour of the storage without insulation.

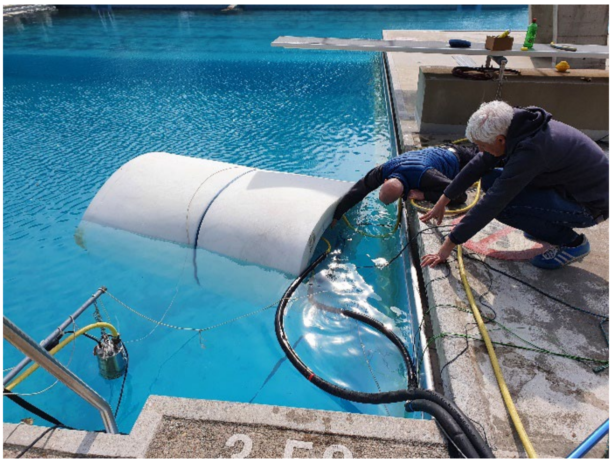


Figure 29: Watering the BILS with the conventional insulation material.

Figure 30: Even after several hours, the insulation does not absorb enough water to sink and return in an upright position.

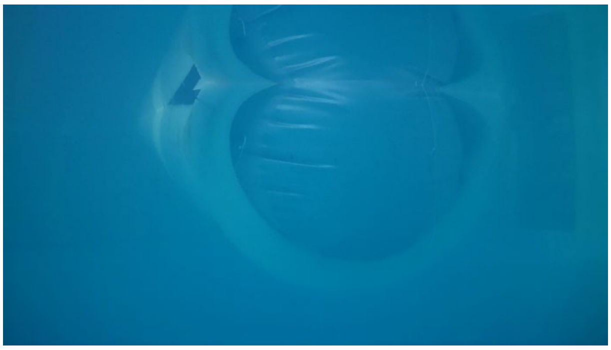


Figure 31: Underwater view of the horizontal BILS with the insulating material.

Indeed, this experiment failed to some extent, as it was not possible to submerge the device with this type of insulation. The assumption that this material can absorb enough water was too optimistic. Even after several hours of watering it was not possible to saturate the material with water. As a result, the buoyancy induced by the remaining air content forced the storage to remain on the surface in horizontal position.

Small-structured plastic materials such as foams are not easily wetted thoroughly. Polyurethane materials are considered in general as hydrophobic without further modification with de-hydrophobic agents. Furthermore, under water small air bubble are created all the time because dissolved gasses in water are released on temperature changes. If this happens inside a porous structure the air bubbles are trapped and will create additional buoyancy. It was assumed then that the coarser open porous blue filter mat should work better as this is used in completely submerged applications (See experiments described in chapters 4.5 and 4.8.5).

Nevertheless, the storage was heated up in this horizontal position. Figure 32 shows the measured temperatures. The test had to be stopped for technical safety reasons. However, it is clear that the maximum temperature difference was higher than for the storage without insulation. As also the uninsulated storage was in a horizontal position, the temperature difference can be assigned at least partly to the insulation, as expected. The temperature measurements must be considered as indicative. The sensors are precise, but it was not possible to fix and determine the position of the sensors due to the tilting of the prototype.

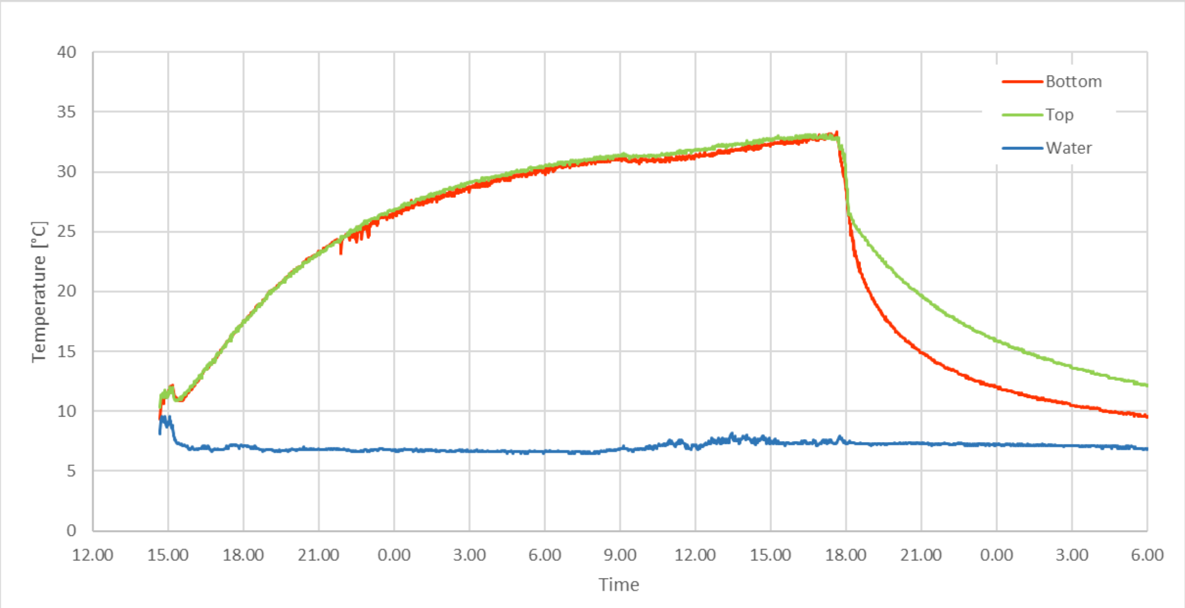


Figure 32: Heating up of the BILS prototype with white insulation

The most important finding and conclusion from this experiment is that the wettability of porous materials must be considered if they are to be used as side insulation. If the insulation cannot be immersed, it cannot be used as side insulation for a BILS. However, the experiment also showed that wet insulation has a positive effect on temperature losses compared to no insulation. However, a quantitative statement is not possible as the insulation was not completely wetted.

4.8.3 Submerged BILS using saline water

In a further series of tests, the possibility of submerging a hot BILS using saline water was investigated. According to theory, this is possible, but verification was helpful and important. The objective of this experiment was to verify the computations made in chapter 4.4 and to understand the general behaviour of a BILS with saline water.

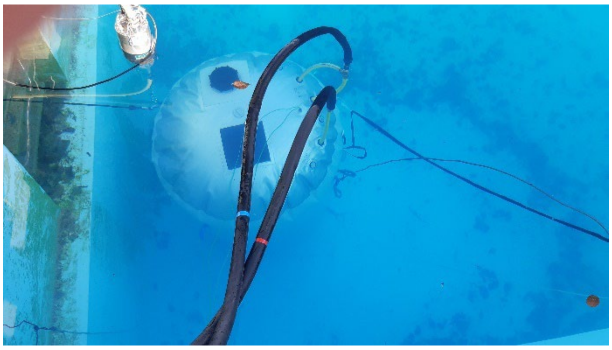


Figure 33: Cold BILS with normal water inside

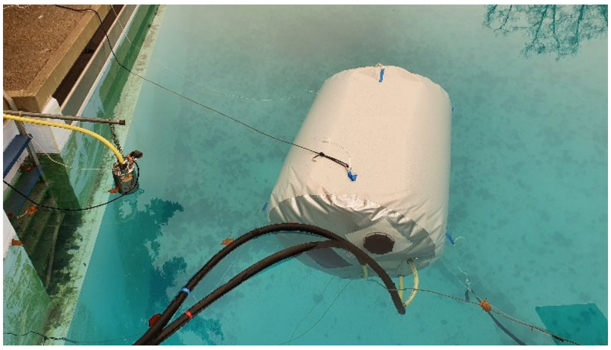


Figure 34: BILS heated up to about 20°C (pool temperature 8-9°C). BILS in surfaced horizontal position

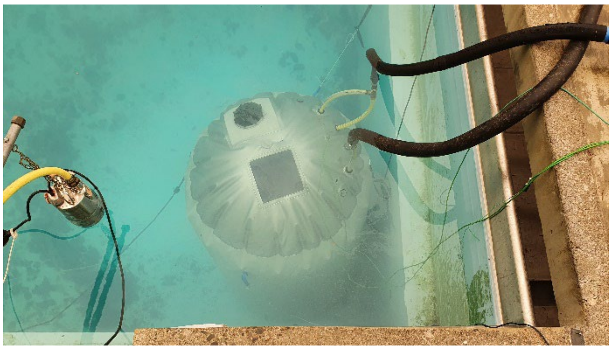


Figure 35: By adding salt to the heating loop the salt concentration inside the BILS is increased until it sinks and goes back in an upright position.

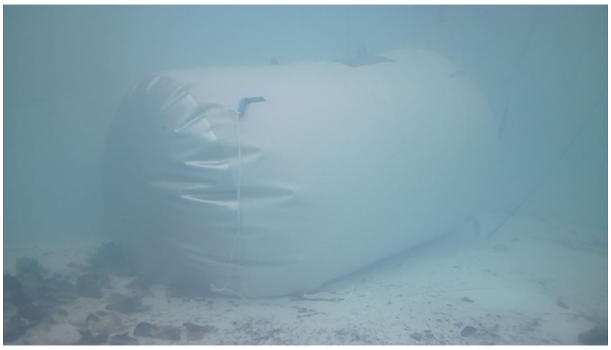


Figure 36: Adding more and more salt increases the density and at some point, the BILS will touch ground and tilt there again.

The temperature inside the BILS was kept stable at about 20 °C and the salt concentration was increased by diluting normal NaCl into the open heating loop. At some point the BILS started to sink again and to come in an upright position again. Within a certain range the buoyancy is close to zero and the BILS will remain upright and tend slowly either to the surface or to the ground. Adding more salt leads to the situation where the storage density is clearly higher than for the surrounding water, so that the BILS is forced to tilt again, but now to the ground (Figure 36).

The main learnings of this experiment are that by adding salt it is possible to submerge a hot BILS. If the concentration is too high (or the temperature too low) the storage sinks to the ground. This is a problem as there are seasonal temperature changes in the BILS and in the lake. This means that the salinity would have to be controlled which is not easily possible and desalination always requires a lot of energy. Other options such as anchoring, or air cushion are also possible but require considerable technological efforts. Without this control of buoyancy, the BILS would sink to the lake ground, which must be avoided to avoid damage to the storage and to the life on the lake ground.

4.8.4 SAP as insulation material

The objective of this test series on SAP material was to better understand the behaviour of this material in relation with the intended use as insulation. Important parameters such as the needed concentrations, the mechanical properties or the temperature stability are not known to the project team.

As found in chapter 4.5, super-absorbents SAPs are considered as the most suitable material to immobilize water. To proof the suitability some simple samples were prepared (Figure 37). The concentration was set just to saturate the mixture. This sample was then boiled for several hours, cooled down and heated up again several times in boiling water (Figure 38). The structure or the performance does not seem to suffer from these temperature cycles. After some time in boiling water part of the material has changed appearance and has become a jellylike consistency that is more or less transparent (Figure 39). Even then and when hot, the sample glass can be turned upside down without loss of water or material.

Figure 37: The SAP material with water absorbed

Figure 38: The sample was cooked in boiling water for several hours

Figure 39: After some time, the granular consistency is turned into a transparent jelly (hydrogel) consistency (bottom).

Figure 40: After some weeks, the water evaporates and leaves back the powder stuck together in some larger pieces. Adding water again will fully recover the material and return to the initial state and consistency (as Figure 37).

After these cycles, the material was left unattended for several months so that it dried out again completely (Figure 40). Adding then some water returns the sample to the initial status. Other samples were frozen for some cycles. The result was the same and the material properties remain apparently unchanged.

The main learning is that the material has the perfect properties for our purposes: It is temperature resistant to at least 100 °C, it can withstand freezing and it is reusable as often as needed. The consistency of the material can be adjusted by the amount of SAP powder, so that also the mechanical stability and flexibility can be adjusted to some extent. The use of the material in agricultural-, food- and medical-industries prove its ecological safety.

4.8.5 BILS simulator for testing insulation materials

The objective of this test series was to develop a device that allows to investigate and to compare the properties of wet insulation materials. There is no experience with wet insulations, especially not with SAPs and no data are available.

To further investigate the behaviour of wet insulation, which could be of interest for BILS, a BILS-simulator has been set up. The main purpose was to simulate a hot interior (storage tank) separated from the simulated cold lake by a wet insulation. After heating the reservoir under controlled conditions, it is possible to compare different materials based on the measured temperature curve inside the reservoir.

The test setup is shown in Figure 41. The lake is connected to a temperature-controlled loop. On one side this allows to emulate an infinite temperature sink (=lake), but also to make sure by appropriate pumping that the water is not standing but continuously in motion. The storage was heated up using a coil heater up to the desired temperature. Inside the storage it is reasonable to assume that the water is standing. This is why the water was not pumped, but an immersion heater was used instead. The insulation material to be tested was placed in between enclosed in a thin plastic foil to avoid convection or exchange of water between lake and storage. The sides of the device are well insulated to minimize heat losses that would affect the measurements.

For sure it is not possible to make with such a device precise measurement of the thermal conductivity or of a U-value. The intention was to compare materials.

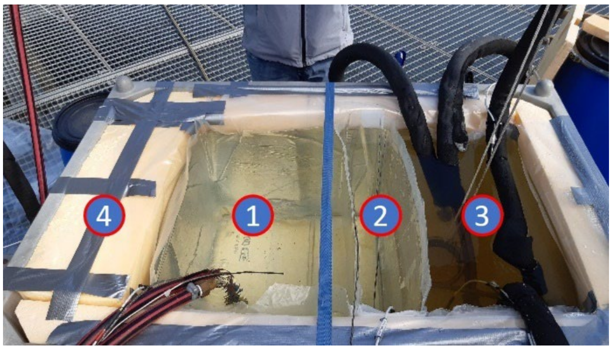


Figure 41: Test device for BILS insulation materials

1) Simulated Lake
2) Insulation material to be tested
3) Simulated hot storage
4) Side insulation

Figure 42: The closed container during insulation tests.

Figure 43: Testing of the blue PU filter foam

Figure 44: Testing the SAP Material, preparation of the insulation sample

Figure 45: The SAP insulation (red arrow)

The tests were carried out for different materials, but with a clear focus on a better understanding of the performance of SAPs in comparison with the other materials. For this purpose, the storage tank was heated up to 60 °C and the lake was stabilized at 10 °C. Apart from the insulation, the rest of the system was not changed for the different materials. At some point, the heating was switched off and the temperature drop in the storage tank was observed as a function of time.

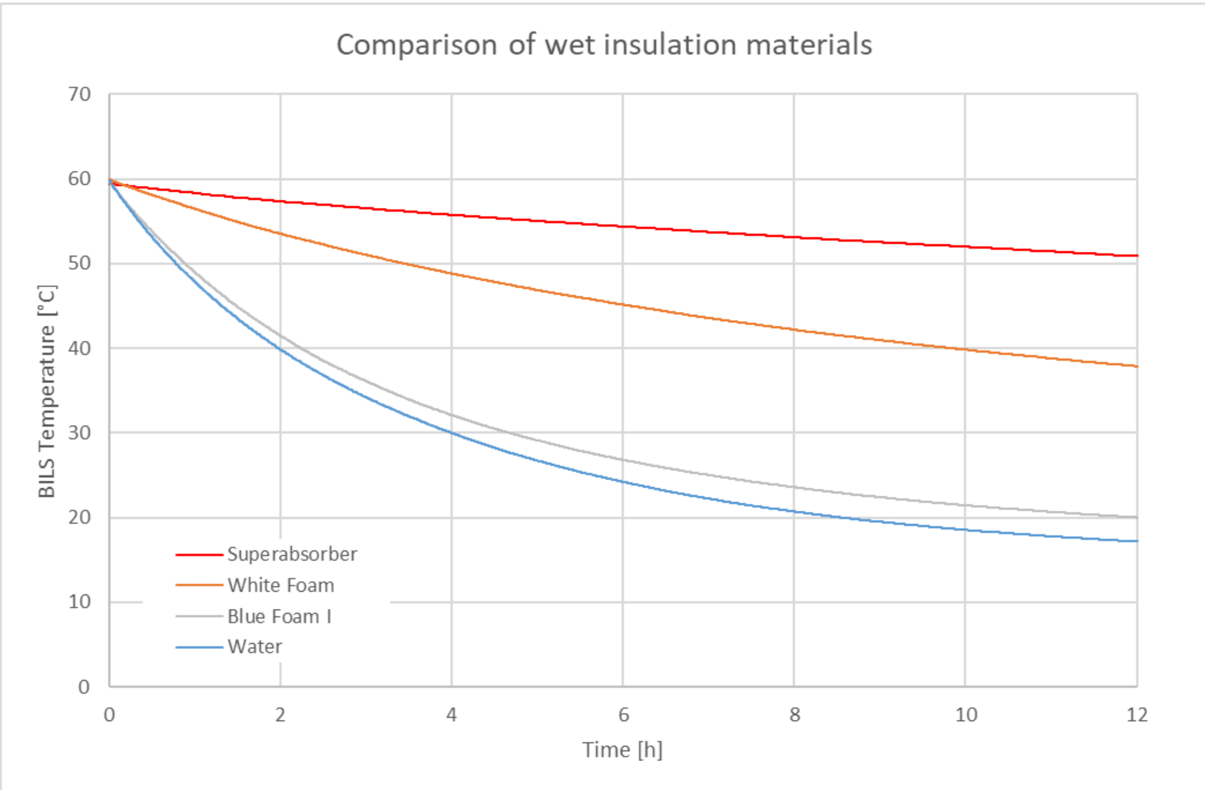


Figure 46: Comparison of the measured temperatures losses for different insulation materials

The result is very promising and confirms the suitability of SAPs for insulation purposes (Figure 46). Obviously, the open-porous PU filter material is only slightly better than pure water. A better result was actually expected, but it clearly shows how important it is to prevent any currents/convection inside the insulation material. The blue PU foam has practically no influence on the thermal behaviour compared to pure water. The conventional white polyurethane foam used as insulation material for hot water storage tanks is much better. Of course, the material has been immersed and wetted as much as possible. From experience, we must assume that despite all efforts, there is still residual air in this insulation. But even then, the SAP sample performs better. The reason for this is most likely that the SAP completely fills the available space. When using a self-supporting material such as PU foam, it will never completely fill a given space, especially if that space is flexible, as would be the case with a BILS. Water will therefore always have the possibility to flow alongside the insulating foam and exchange energy between the warm and cold sides. SAP will adapt to a given shape much easier than other materials.

4.8.6 Open PU as BILS shell material

The objective of this test was to better understand whether the blue PU foam would be submersible as expected. The main advantage of this material would be its form stability that would reinforce a BILS insulation structure that is made only of SAPs. This experiment was done in Rapperswil in the lake of Zurich.

To better understand the possibilities and the behaviour of the open cell PU filter foam, a hollow non-functional dummy BILS was built by enveloping a single piece of the insulation material of 1 m x 2 m with a thickness of 0.1 m with a plastic foil. This device has a diameter of about 0.6 m outer diameter and a length of 1 m. This device was then brough to the (real) lake (Figure 47).

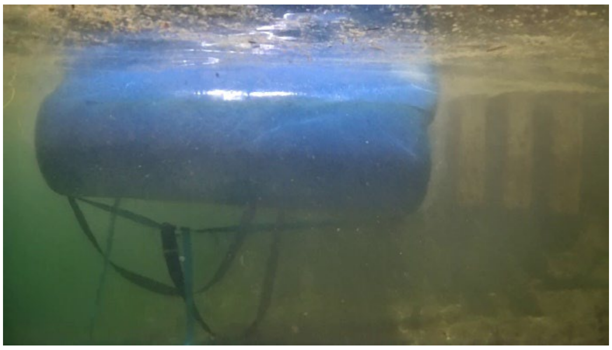


Figure 47: Under water side view of the PU BILS dummy.

As seen before, the insulation properties of the PU-material are not worth to be further investigated. The nice property of this material is however, that it is rather stiff but still flexible. It could therefore provide a flexible but still dimensionally rather stable envelope for the BILS. Using only SAP insulation without making sure to keep the shape of the insulation will probably not work in a wavy water environment. The test showed that the shape is retained even after severe deformation.

Despite its open-cell structure, the material we used obviously has a lower density than water, even after several hours of immersion. For this reason, the device was always swimming at the surface in horizontal position even when completely wetted.

The approach could however be of relevant help in bigger devices again because of its dimensional stability (See also chapter 4.8.7). For sure the material can be designed such as to have also a higher density. PU is also considered as one of the chemically and thermally stable materials for the use in water. A combination of the of PU foam material with SAP could therefore be an interesting solution. By saturating the PU foam with SAP and water, the insulation properties of water could be combined with the dimensional stability of the PU foam.

The main problem is most probably the cost of the material and the available shapes. The cost for the sample used for these experiments was in the range of 200 €/m^2 for a 10 cm thick sheet. Thicker sheets do not seem to be easily available as commercial goods. An insulation thickness of 2 meters would therefore already lead to cost in the range of more than 4000 €/m^2.

The main conclusion of this short experiment is that even such open porous foams are not easily wetted to such an extent that they start to submerge (See also chapter 4.8.2). If this is not possible, the whole storage has the tendency to swim on the surface in a horizontal position (See also chapter 4.8.1).

4.8.7 BILS with SAP insulation (Prototype I)

The objective of these experiments was to build a first BILS prototype with SAP as insulation material. SAPs have a jelly-like structure so that they have to be enclosed in a structure to make sure that the thickness of the insulation remains uniform. A flexible double wall structure with SAP in between would most likely not work and a homogeneous distribution of the material is not guaranteed. Therefore, the use of commercially available SAP water pockets was investigated to simplify this containment.

The use of SAP as insulation material was further investigated in the following series of experiment in the frame of a student work at SPF [16]. As mentioned before in this report, SAPs are used in packing and transport applications. With the intention to use commercially available products we decided to use so called ice packs that are used to transport goods like fresh fruit, fish or flowers. The content of these Ravioli-type bags is a small amount of SAP in dry status (Figure 48). The envelope is perforated with very small holes allowing water to penetrate while still enclosing the SAP powder. The bags are submerged in water and will soak up a certain amount of water within a few minutes (Figure 49 and Figure 50). The bags can then be cooled down and also be frozen. The bags are added to the transporting goods to keep them cooled instead of ice cubes. The main advantage is that even when melting, almost no water is released to the transport container. The bags can be reused and refrozen an unlimited number of times. These bags are rather cheap and easy to handle. The idea is to use these commercially available products to build a BILS insulation.

Figure 48: The bags as purchased and unfilled.


Figure 49: After soaking up the bags are still flexible, but the material is well enclosed inside.


Figure 50: The water saturated SAP material inside the water bags.

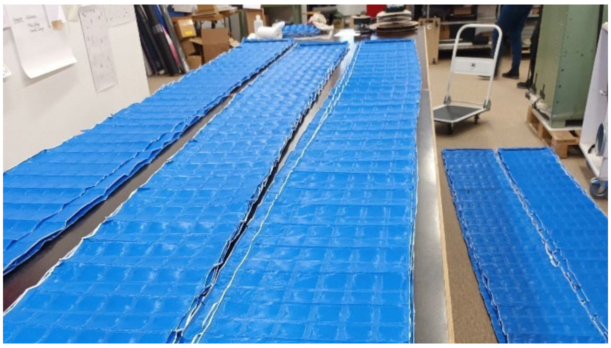


Figure 51: Several meters and layers were wrapped around the BILS container that was also used in earlier experiments.

Several meters of these packing bags were wrapped around the already existing BILS prototype and fixed to create an SAP insulation. This BILS prototype was tested again in the public swimming area “Zwischen den Hölzern”.

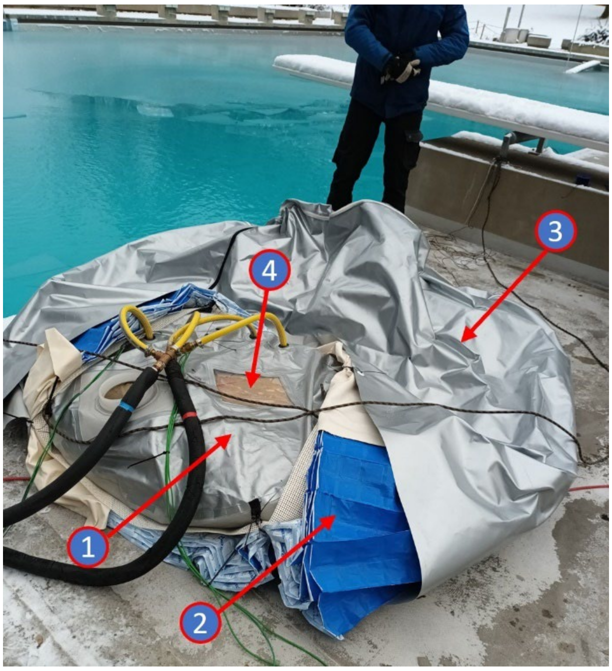


Figure 52: BILS prototype with SAP water bags before watering

1) The central BILS container
2) The dry SAP bags fixed to the central container
3) Additional outer envelope to enclose the insulation
4) Top insulation inside the container.

Figure 53: The whole BILS prototype including the dry insulation is watered.

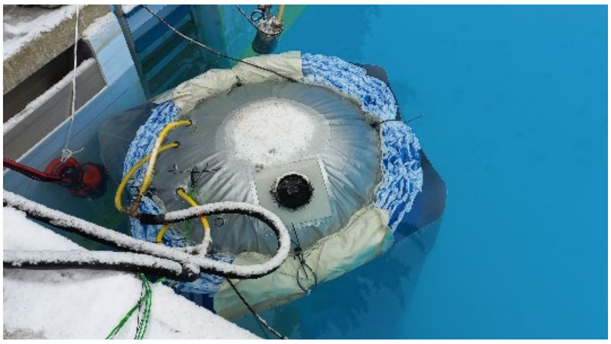


Figure 54: After filling the inner storage and after wetting the SAP bags, the storage is in it expected shape.

Before watering, the waterbags are dry and easy to transport (Figure 52). When entering the water, the bags start to absorb water and to swell up. After some time in water the whole prototype has come then into the expected shape (Figure 54). An outer sheet was added compared to the previous version, as well as an insulation on the bottom and on top (inside the inner bag). On top a layer of conventional PU-foam was used (Figure 52) and on the bottom a bigger SAP-bag was used as insulation. These are not visible as they were mounted inside the storage.

The prototype was heated up as before with the same heating power of 11 kW. However, the pool was colder at this time with only 2-3 °C. The heating-up measurements are shown in Figure 55. At the beginning, the temperature rise was comparable or even slightly higher than in the previous experiment with conventional insulation material (chapter 4.8.2). At about 1 a.m. heavy snow fall started, and the temperature rise was interrupted. After that, the heating was continued but with a slower rate due to the continuing snowfalls. Shortly after 9:00 a.m., the heating had to be stopped for technical reasons and could not be resumed anymore.

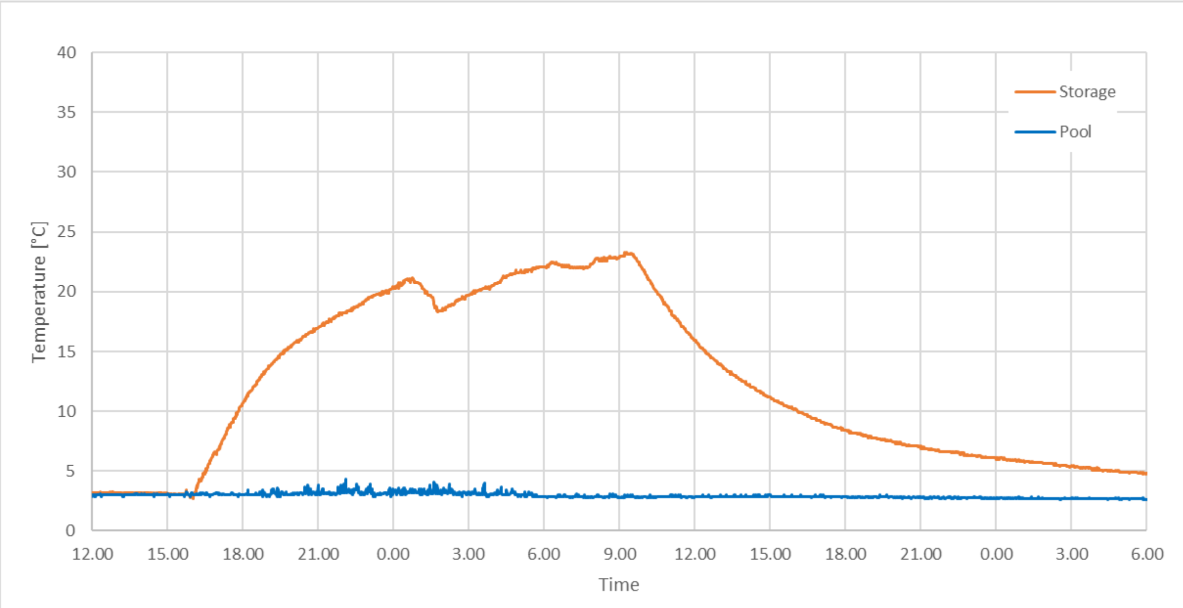


Figure 55: Heating up of the BILS prototype with SAP waterbags insulation.

At this point, the experiments had to be stopped to avoid spoiling the swimming area as the waterbags obviously started to leak slightly.

Conclusions from this experiment.

- Basically, the insulation with SAP materials works, but it is relevant to avoid free floating water between the insulation elements.
- Even if the SAP is considered as harmless, potential leakage must be considered. The commercial water bags used in this experiment are therefore excluded as material for further experiments.
- The heating power of the mobile heater was not sufficient to reach higher temperatures.

4.8.8 BILS with SAP Insulation (Prototype II)

The objective of these last experiments was to merge the main findings of this project in a new prototype. With this prototype, higher temperatures shall be reached and the thermal losses of the BILS with a revised SAP approach shall be investigated.

The prototype with the waterbags showed some weaknesses, especially water flowing between the bags and some leakages of the insulation material. A next version BILS also based on SAP insulation material was therefore designed. For this prototype, another SAP material was used and waterflow in the insulation was minimized by enclosing, comparting and segmenting the insulation. Furthermore, the diameter to height ratio was increased so that tilting of the BILS as a whole was not possible anymore.

The original plan was to carry out these final experiments in a lake to get as close as possible to the later application. However, based on the experience gained with the experiments in the outdoor swimming pool, it was decided to carry out these final experiments in the laboratories of the university. The experimental conditions on a lake are difficult for many simple reasons (where to get sufficient power supply, how to get authorization for such work, high costs for working platforms, safety, etc.). Also, the risk of an accident or loss of the prototype was considered too high compared to the expected gain in knowledge in the current phase.

This prototype consisted of a main tank (made of PVC foil) with a diameter of 1.0 m and a height of 0.8 m, hence with a design volume of about 0.63 m^3. The insulation thickness was planned with a thickness of 0.5 m separated in three segmented rows (Figure 56). The theoretical volume of the insulation was therefore in the range of 1.88 m^3. Figure 57 shows the assembly of the storage in the atelier. As can be seen on the photographs, the third row of insulation was planned, but later not used.

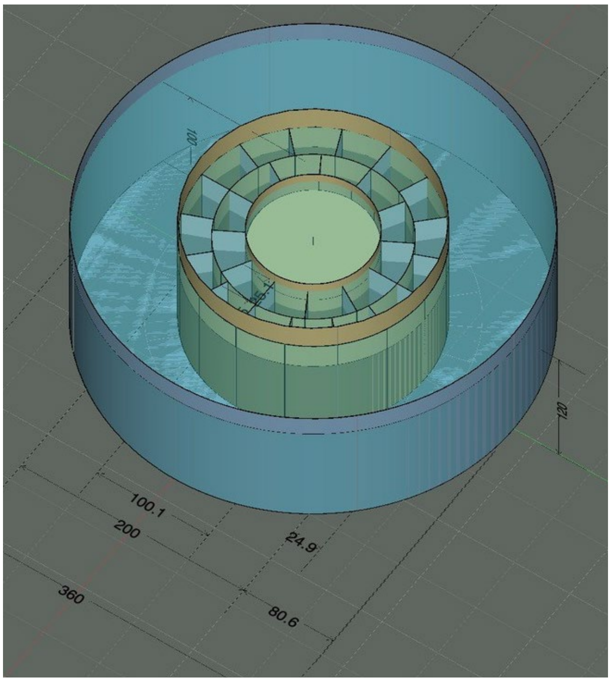


Figure 56: Plan of the SAP insulation prototype. Inner container is the storage. The circular honeycomb structure will be filled with SAP material.

Figure 57: Assembly of the prototype in the atelier.

For the setup (Figure 58) the storage was filled first and the insulation was applied later. Even if the SAP material is immobilized, it is still ductile and flowable. If the insulation was simply placed in the radial segments, the distribution of the material would most likely not remain homogeneous over a long period of time. With the addition circular segmentation, the distribution of the SAP can be controlled. For this experiment, the material was furthermore filled in long bags, mainly to facilitate handling of the material (Figure 59). The long bags were provided with a well-defined small amount of SAP (Kappasorb 230, which was not the same product as used in the previous experiments), then the bags were filled with water and closed on the top. The concentration and stiffness of the bags could be adjusted to some extent by adjusting the amount of raw material.

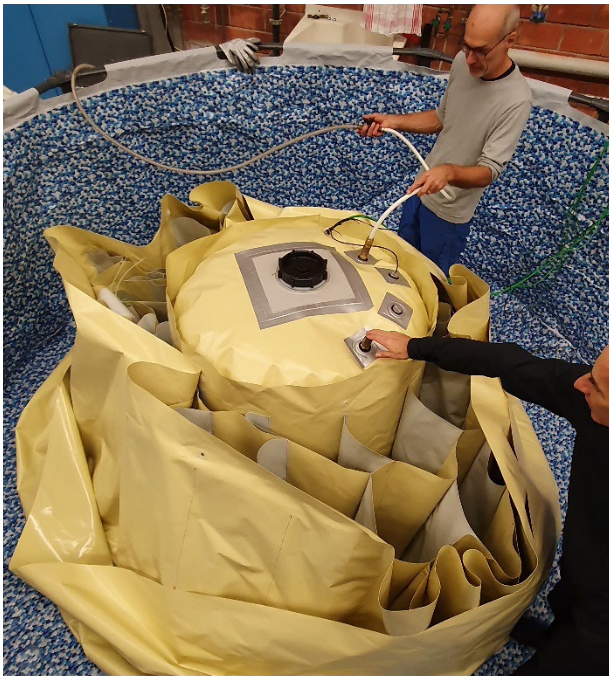


Figure 58: Installation of the prototype, initial filling of the storage in the laboratory.

Figure 59: The SAP material is filled in tubular bags. (Right bag: The dry material at the bottom. Left bag: Immobilized water)

These long bags were then inserted into the honeycomb-like structure (Figure 60). The same bags were used as well as bottom insulation. One layer was placed below the central storage tank (Figure 61). The used of these bags had mainly operational reasons as they are easy to handle. One insight from the previous experiments was that also the dismantling and deconstruction must be planned in due time.

In a bigger BILS, the SAP material would not be intended to be enclosed in additional bags. The honeycomb approach would most probably be followed up and the single combs would be directly filled with the dry material as shown in Figure 59, and then be filled up with water during installation. As an alternative or as an update to this honeycomb structure, the previously discussed use of PU foams in combination with SAPs could help to further stabilize the shape of the whole device.

Figure 60: Insertion of the SAP tubes into the honeycomb-like structure.

Figure 61: Bottom insulation under the main storage is also made of the same SAP tubes.

After assembling and filling the device, the surrounding basin was filled with water to a height of just over 1 m to simulate the lake. For assembly and filling, the prototype was secured from above with a crane (Figure 62), also to prevent the BILS from floating away. The device was wrapped in an outer foil to prevent the surrounding water to flow into the insulation. Furthermore, there were fixing devices, openings, hydraulic connections and tubes, etc. so that the total density was slightly higher than that of water and therefore the device obviously was lying on ground (Figure 63), at least when cold.

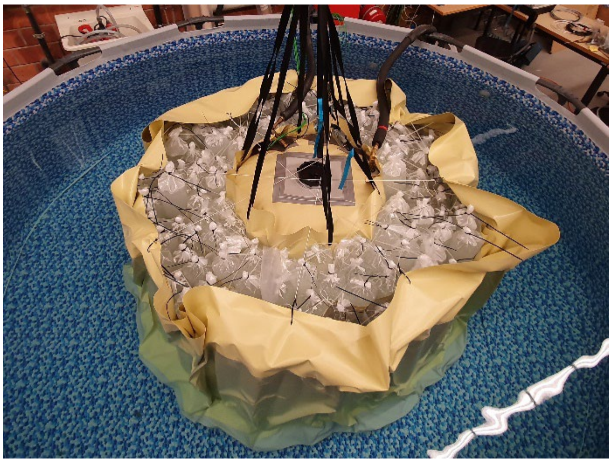


Figure 62: The SAP tubes are inserted in the honeycomb structure. The pool is filled with water.

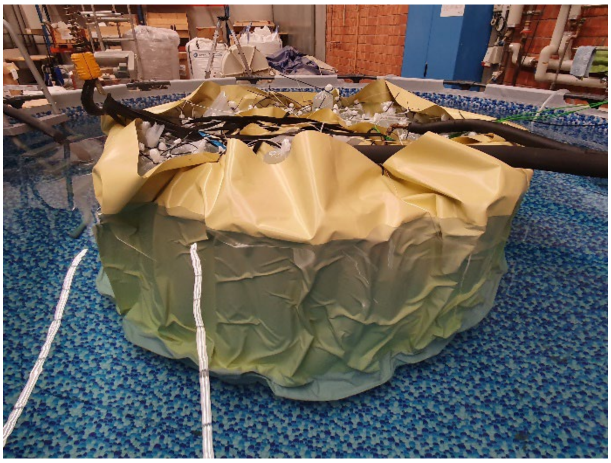


Figure 63: Total density is higher than that of the surrounding water. BILS is on ground.

The main storage in the centre was connected to a heating loop. Several temperature sensors were installed in the centre of the storage: “Sto_T” (Top), “Sto_M” (Middle height) and “Sto_B” (Bottom), and one a the outside “Sto_O”. Furthermore, inside the insulation: “Ins_O” (Outside), “Ins_M” (Middle) and “Ins_I” (Inside). The pool temperature was “Lake” and ambient air was “Amb”. These designations are used in the following graphs. As the whole device was very flexible and not accessible anymore, it was difficult to know the exact position of the sensors after starting up the system. It must also be expected that some sensors displace during the experiment slightly if the BILS was deformed slightly. Fixed positions were not possible.

Figure 64 shows the heating up of the central storage. The maximum temperature setpoint was for technical reasons limited at 67 °C and the modulation of the temperature was caused by the heater controller. The general behaviour was as expected: The inner storage was heated up to a “constant” maximum temperature within about 3 h. After that, the temperature inside the storage was about the same at the bottom and on top. There was for sure no stratification because of the pumped heating loop. The temperatures were increasing very slowly inside the insulation, even after two days of continuous heating, a stable temperature distribution was not reached. The bumps at about 18:00 are caused by the experimenter who was lifting the storage slightly to check whether it was close to a floating status. The heating up of the pool filled with cold water was mainly caused by the approximation to the ambient air temperature but also by heat losses of the storage.

All in all, the behaviour was as expected for an insulated storage tank. For time constraints, the sequence was stopped after 06:00, even if the temperature distribution in the insulating material did not yet reach a stable state.

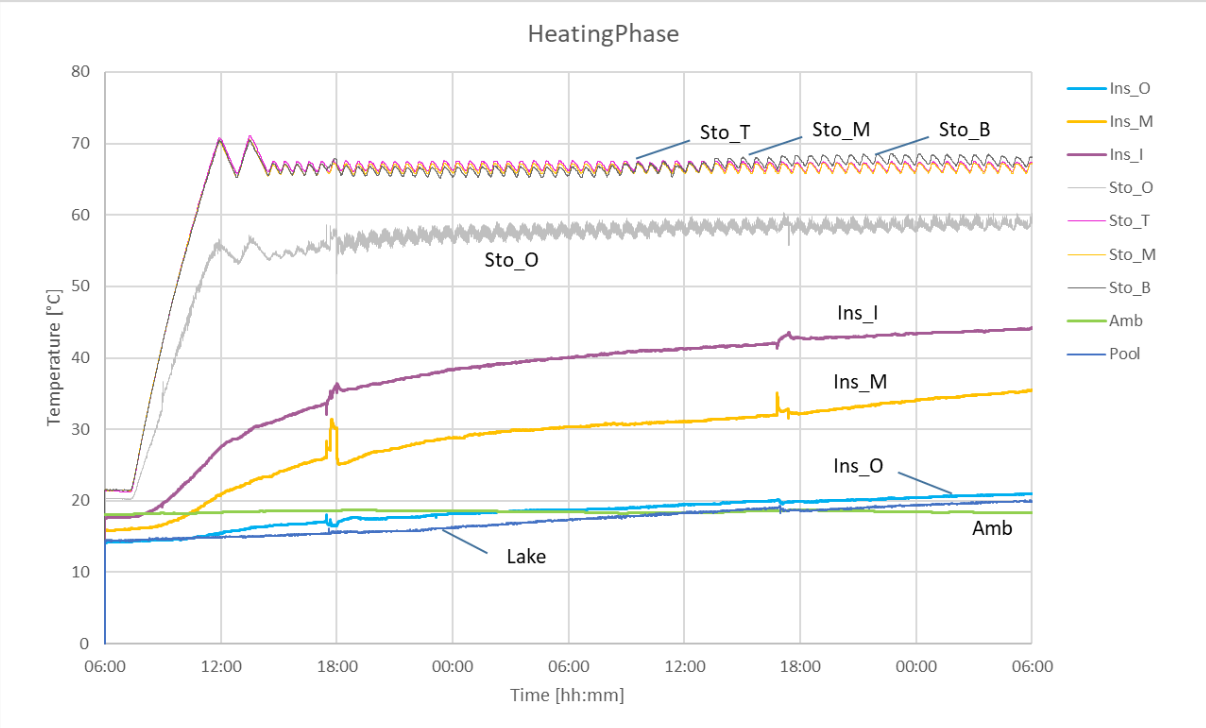


Figure 64: The measured temperatures during the heating up phase of the SAP prototype.

At 06:00 the heating and the pumps were switched off to observe the cooling phase (Figure 65). The bottom of the central storage was obviously losing energy and the temperature drop (Sto_B) was much higher than at the middle or the top (Sto_M and Sto_T). Obviously, the bottom insulation was too weak, and we assume that there was also loss of SAP and ingress of water from below the storage. This should be improved in a next version. Interesting, was the significant difference between top and bottom, obviously the top losses (to air, no insulation) were much smaller than the bottom losses. Even if the losses were high at the bottom and the top, it took about two days to cool down the storage, which was already much better than in previous experiments.

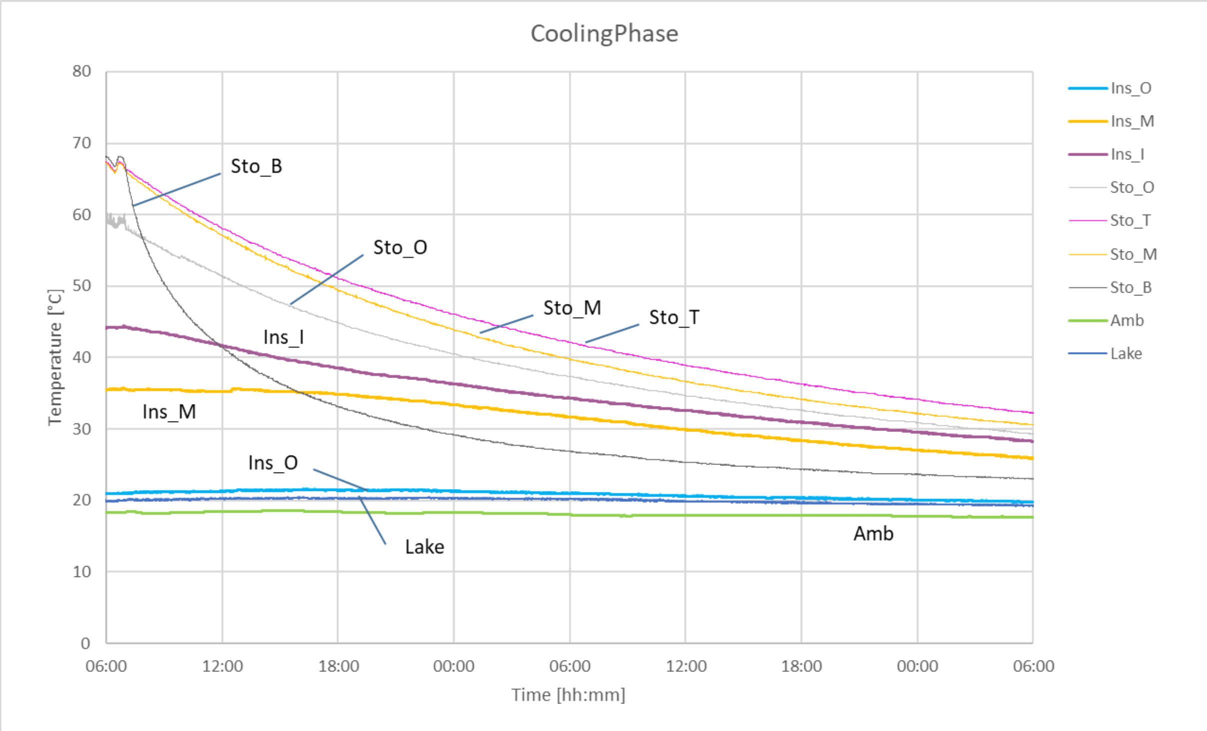


Figure 65: Cooling down phase without heating and pumping.

With this experiment it was possible to confirm that water as insulation material works when immobilized with SAP. Several points need to be further improved, but the basic concept is confirmed.

In a next experiment, the impact of water currents and waves was investigated. The same setup was used with the known weaknesses, but the surrounding water was animated by submerging three diving pumps in the pool. As can be seen in Figure 66 and Figure 67 the water surface is troubled by the strong underwater currents.

Figure 66: The same SAP prototype, but the water in the pool is being moved by several submersible pumps

Figure 67: Side view of the SAP prototype in the pool with turbulent water.

The storage was heated up as before (Figure 68) and after one day (indicated by the red arrow) the submerged pumps were started. The small immediate changes of the temperatures must be attributed to some displacement of the sensors in the animated environment. Obviously, the temperature at the bottom (Sto_B) is starting to decrease, meaning that there is also some water flow under the storage. The event that is visible in the temperature measurements at about 1:00 a.m. is not known.

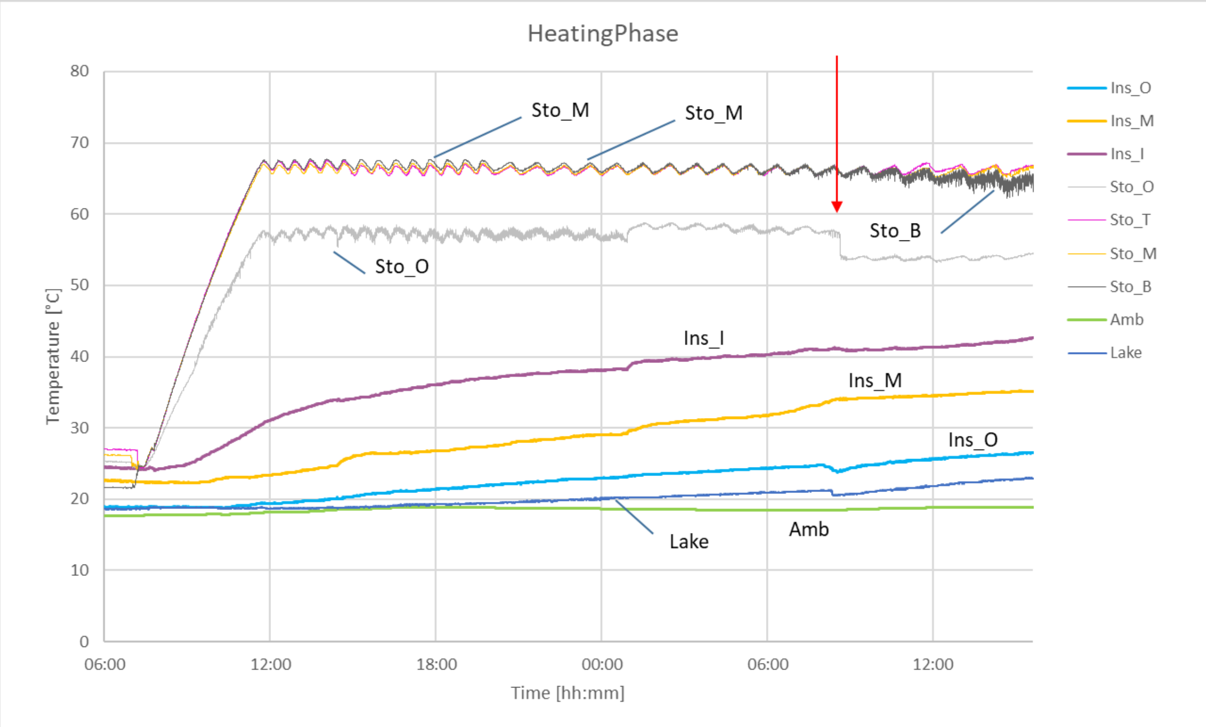


Figure 68: Heating up again the SAP BILS. At about 8:00 of the second day (indicated with the red arrow), the pumps in the pool were started to create waves and currents.

Even if no stable temperature gradient in the insulation was reached in a short time, the experiment was stopped, meaning that the heating and pumping of the central storage were switched off. The pumps in the pool used to simulate waves and currents of a lake, were not stopped.

The temperature measurements (Figure 69) show a significant difference to the measurements with a calm pool. Compared to the calm water, the heat losses were much higher than before especially again at the bottom, meaning that there was water flow below the storage even if visually the storage seems to be on ground.

To better illustrate the difference, only the temperatures of the storage centre (Sto_M) for the calm and the animated pool are compared in Figure 70 and plotted on the same time scale. The initial temperature was 65.5 °C in both cases. The additional energy losses are obviously much higher in an animated environment. This difference may be attributed to various effects, such as the currents inside the tank, the movements in the pool, the currents under the BILS where the insulation is insufficient, etc. But also, other effects such as the expected increase in heat transfer coefficients between the BILS and the surrounding animated water should also be considered and be further investigated.

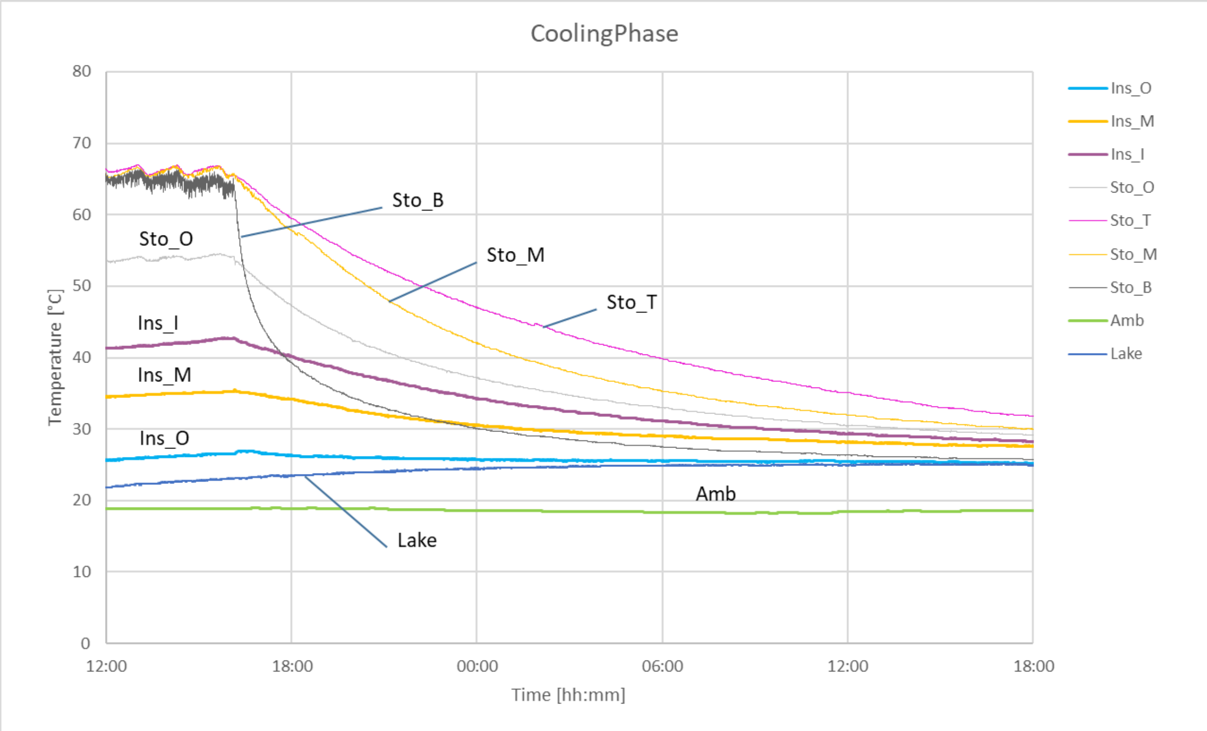


Figure 69: Temperature measurements during the cooling phase in an animated pool.

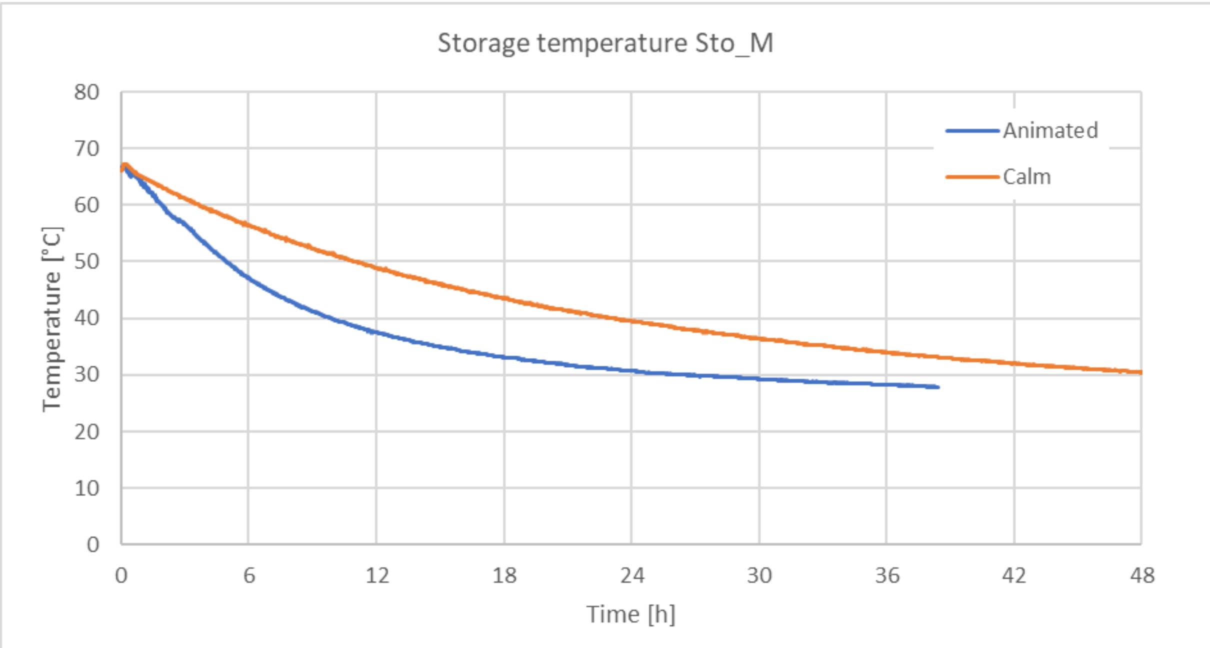


Figure 70: Comparison of the measured temperature decay in the centre of the storage when the BILS is in calm and in animated water environment.

The most important finding from these last tests is that the BILS concept with SAP insulation obviously works. However, it is important that the insulation is also sufficient on the underside (and on the top). It can also be confirmed that water flow can have a significant impact on heat loss. A similar BILS with reinforced bottom and top insulation and with more layers of side insulation would be the next version to be tested in a lake if additional resources were available.

4.9 Exchange with experts

The BILS concept was discussed with scientific colleagues of the institute and from other universities, and during the SWEET events that took place in the last two years. The idea was also presented in different events and the feedback was discussed. Based on such discussions new ideas have been developed or ideas have been discarded. These cannot be listed in detail but are a relevant part of the work.

The BILS idea was also shared and discussed with several experts in the field of large thermal storages, pit storages and dedicated materials for such devices. The most important external contributors for this project are listed below:

Florian Ruesch	SPF Institute for Solar Technology (Expert in thermal storages)
Andreas Zourellis	Vice president technical sales, Aalborg CSP (DK)
Geoffroy Gauthier	Civil engineer Planergi (DK)
Markus Seume	G quadrat GmbH
Gernot Wallner	Johannes Kepler University Linz
Franz Luhamer	agru Kunststofftechnik GmbH
David Nitsche	agru Kunststofftechnik GmbH
Simon Furbo	Technical University of Denmark, Kongens Lyngby (DTU)
Ioannis Sifnaios	Technical University of Denmark, Kongens Lyngby (DTU)

The main aim of contacting these experienced experts was to scrutinise the idea and the concept in general. But also, to better understand which technologies are used in today's heat storage systems, what could be adopted for the BILS concept, what is considered a major challenge, what experiences can we learn from, what would be needed to build larger prototypes and, of course, to establish a network of experts and companies that will be needed for larger prototypes in the future. Not all information can be shared as some is considered confidential or is related to ongoing other projects.

None of the contacted experts has seen an unsolvable problem with the concept and there is interest in follow up projects or to contribute when building larger prototypes. Many of their ideas and inputs were similar to what was already ongoing or planned in the project, such as for example, the idea of using saline water to submerge the storage.

The main results of these interviews are related to the material selection of the envelopes. The liners used for pit storages are made of high temperature resistant Polypropylene (PP-HTR) and polyethylene (PE-HTR). The lifetime is very much depending on the intended temperature range and on the number of hot-cold cycles. For PP-HTR, a lifetime of 25-45 years can be expected in a pit storage. The material composition can be adjusted, and the companies are available in Europe that can produce such materials in large quantities. The methods for predicting the lifetime of these materials are developed and available for example at the Johannes Kepler University in Linz. For specific applications such as for a BILS, the material would have to be designed accordingly and tested for the specific environment. This would require additional research together with manufacturers of these liners.

The production methods that are currently used, cannot be adopted as they are, and would need to be further developed. Pit storages are manufactured starting from the raw material, usually supplied as sheets of 7 m x 100 m, which are then assembled on place using special plastic welding methods. This welding requires dry places and dry materials and a certain ambient temperature range. The problem is considered as solvable, but the current technologies must be adopted and be further developed, depending on the size and structure of the device. On the other side, there are also very large plastic devices (for example used in fishing industry[7]) that are assembled offshore and then transported as a whole to the intended place of use.

According to my understanding of the experts, the choice of materials and production methods are issues that require technological development, but which are also seen as solvable.

4.10 Discussion

Many people have contributed and provided ideas, suggestions and calculations. In this case, however, it was also very important to have the opportunity to conduct experiments to verify and challenge ideas and assumptions, but probably even more so to analyse and understand unexpected results. Starting from the pit storage concept, where thermal insulation is considered a solved issue, we had to learn about the importance of thermal insulation in any underwater storage. These very relevant differences were not clear and therefore very quickly led to the search for insulation material becoming a central topic of the project, consuming many more resources than expected. The topic of buoyancy and the density of insulation materials are very closely linked, so that this topic also had to be given much more attention than expected.

Large thermal energy storage systems are attracting increasing interest, also in Switzerland. Half of the country's energy requirement is heat and district heating is constantly growing[8] [4],[5]. The current options for large heat storages are limited, so that new solutions need to be considered. In this project, we have shown that BILS can be one of these new options.

5 Conclusions

The BILS approach is technically viable and should be followed up. The realization especially at larger scale will not be as simple as it was expected at the beginning. The experiments showed that going to larger scale in a lake will require much more technological efforts than expected. A simple example is the mass that must be handled in the lake: The prototypes we were using, were in the range of 2000 – 3000 kg. Even if this was floating, the handling required often several strong persons. A larger example with, for example, 10 m^3 core storage volume and 2 m of insulation, which could be a reasonable next step, would already have a mass of around 45 t. This requires heavy platforms and specific construction equipment that is not easily available for a research institute. Other issues such as

[7] https://bluegreengroup.no/en/services/marine-donut

[8] https://www.bfe.admin.ch/bfe/de/home/versorgung/energieeffizienz/fernwaerme.html

the energy needed for heating up, the safe installation and handling, the later disposal, etc are technical challenges that will require much more resources than expected.

However, to the current stage, no unsolvable technical problems have been identified. For sure some additional topics need to be addressed such as the mentioned material selection of the envelope or the manufacturing process. Linked to this are other technological questions such as the anchoring, mode of operation or the heat exchangers to be used. But also, some non-technical challenges must be expected such as the general acceptance of the society to place bigger technical devices in a lake. Also, legal issues and concerns about the biological impact on the lake need to be clarified in more detail, even if care was taken, to exclude all materials that are supposed to be problematic for the environment. These questions need to be addressed before the next step can be taken, which is to go into the lake with a prototype. This is now possible, as it is clear how the next prototypes are supposed to be designed.

The main finding of the project is that flexible storages in lakes can be a solution for placing large thermal storages in lakes. By using immobilized water as insulation material, the insulation and the buoyancy topic can be solved. To the authors best knowledge, the idea of using water as insulation material was never considered seriously. In this project it has been demonstrated that this is possible under the condition that water is immobilized and that the thickness of the insulation can be increased as necessary, which is possible for a very big storage only. It is not a solution for small storages. A solution has been found to immobilize water with low-cost materials and with properties that are matching the requirements of a BILS.

In an environment with natural convection and currents, such as a lake, the mixing of the storage tank content must also be reduced to minimize heat losses. We assume that this can be achieved by dividing the internal storage tank into different compartments. Other approaches are also thinkable, such as for example completely filling the storage tank with SAP to prevent water movement. These questions require further experimental work and investigations using FEM and CFD methods. The further reduction of the heat transfer coefficient to the lake is also a topic of interest. One idea is to cover the BILS on the outside with seagrass or other plants to create a boundary layer of calm water around the outer envelope of the BILS. This approach would resemble the honeycomb idea developed earlier (chapter 4.5).

For sure the experimental work was particularly important and highlighted some of the problems to expect when realizing bigger devices. As an example: At some point, bigger BILS will not be transportable anymore and will have to be manufactured on the lake. A similar question will be the procedure for dismantling at the end of life. The methods used on this project (i.e., build the BILS in the laboratory, transport to the lake and fill it with water) will not work and new methods must be developed. Even more challenging is the dismantling and/or the repair work if needed. There are still many technical issues to be clarified before a commercial phase is reached.

Following the discussions with experts, the material of the outer envelope is surprisingly not considered to be a major problem. Appropriate materials are widely used in different disciplines of pit construction. Materials and different technologies are adoptable with some effort to BILS from these industries. As an example, there are already leakage detectors and leakage location system available that could be used also for BILS.

Also, some other topics have not been further investigated as apparently there are already other industries where solutions have been developed. As an example: We have not specifically worked on the mooring of BILS as there is fish farming industry where solutions for anchoring big flexible devices are already available. The same applies for the integration and operation of the BILS in district heating systems. There is expertise available, and this is not a specific BILS problem and therefore this was not further investigated.

The concept that is currently considered the best, is very similar to the one that was tested as the last prototype (chapter 4.8.8). If there were more resources for experimental work and for further development, a similar prototype would be the basis to develop some improvements for the assembly and the general handling of the SAP insulation and to further reduce heat losses. This would require going back into deeper standing waters, by preference a lake, also to investigate and better understand the impact of waves and underwater currents on the BILS. In parallel it is important to digitally model the storage to reduce experimental efforts for example for the development of the inner structure of the storage.

6 Cooperation and coordination with SWEET consortia and SOUR projects

There were interesting discussions during the SWEET programme events with representatives of other SWEET and SOUR projects. Namely the integration into networks, on legal questions, but also on technological items. The engineering and experimental nature of the project is however quite different from the work done in the typical SWEET consortia. No concrete collaboration within the SWEET programme was set up during the course of the project, which is also due to the low TRL level of the BILS concept.

7 Outlook and next steps

The experience and the experiments in this project are very important, as no previous experience or expertise was available. However, it is also clear that only a first step was possible with the current project and that many open questions have been raised that need to be addressed and resolved before a P&D project can be considered.

The concept will therefore be further investigated in the frame of a follow up project “SwissSTES - Swiss Seasonal Thermal Energy Storage Action Plan and Implementation” Flagship 107.395 FS-EE (Innovation project as part of the Flagship Initiative) where a work package for BILS is allocated. In Subproject 7 of SwissSTES, several technological and environmental aspects of the concept are investigated to pave the way for a first P&D demonstrations project. By using advanced FEM and CFD simulations, a better understanding of the mechanical and thermal behaviour of the BILS is expected. Also, other shapes than cylinders could be investigated. These simulations will provide clarity for material selection, mooring and thermal performance. However, the resources for more experimental work are not available in this project, and a supplementary project would be required to experimentally test different ideas to improve the concept and to verify the simulation work.

Partners in this SwissSTES project will also include companies that specialize in construction work in waters. They have the knowledge and expertise not only for the construction work, but also for the legal and environmental conditions for such projects.

The interest in BILS has also been received from different energy suppliers. In the frame of the SwissSTES project, the potential integration of BILS in thermal networks will be investigated in the two case studies called “Zurich” and “Ausserschwyz” in Subproject 10.

8 Outputs and outreach

Public oral and visual presentations (scientific or broad audience)

Project partners	**Description:** author(s), title, name of the event and location, year of presentation
SPF	SWEET Conference 2022, ‘Kulturschüür Uptown’ Gurten Poster presentation, Bern, 15. June 2022
SPF	SPF-Industrietag, Eastern Switzerland University of Applied Sciences (OST), Poster presentation, Rapperswil, 15.6.2022
SPF	Oral input presentation for the “Fachkommission Elementarschadenregister» of the Association of Cantonal Fire Insurance Companies ACFI, 22. June 2022
SPF	SWEET DeCarbCH Lunch Talk – SOUR, Online presentation, Andreas Bohren 10.01.2023 DeCarbCH Lunch Talk: Bubble in the lake, big thermal storage underwater? https://www.youtube.com/watch?v=0I1fUgM0wIo
SPF	Veranstaltungsreihe «Klimaneutrale Schweiz 2050» von Swiss Engineering Sektion Zürich und Swisscleantech zum Thema Saisonale Energiespeicherung – Schlüsselelement für eine erfolgreiche Energiewende. Oral presentation, Rapperswil, Andreas Bohren 17.05.2023
SPF	SWEET Conference 2023, Eventforum Bern Poster presentation, Bern, 06.09.2023

Other outputs

Project partners	**Description**: brief description of the outputs.
SPF	Seasonal Energy Storage: Thermal Energy Storage in Lakes Semester project at the Eastern Switzerland University of Applied Sciences (OST), Rachel Anne Freeman, 30 December 2022
SPF	Webpage www.bils.tech

9 Acknowledgements

Many thanks to Urs Meier Aegler and his team from Luft & Laune and to Alfred Brunner. Only with their expertise and their untiring commitment - even under cold and harsh conditions - the experimental work was possible.

Special thanks are owed to the Department of School and Sport of the city of Zurich which provided access to the public swimming area “Zwischen den Hölzern” in Oberengstringen close to Zurich. Experiments would have been difficult without this highly appreciated and valuable support.

Many thanks also to Rachel Anne Freeman for her engagement and for the results of her semester project.

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