SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Technical report on best practices for energy storage including both efficiency and adaptability in solar cooling systems

IEA SHC TASK 53 | NEW GENERATION SOLAR COOLING & HEATING SYSTEMS (PV OR THERMALLY DRIVEN)

Technical report on best practices for energy storage including both efficiency and adaptability in solar cooling systems

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Introduction

The gravity centre in energy research and development is shifting from centralized production to the level of building neighbourhood, district and urban systems that bring together a variety of classical research topics such as energy management, as well as the production of heat/cold and of electricity via renewable and non-renewable technologies, electricity distribution networks, thermal networks, energy demand in buildings into one integrated system. Thus, a strong need to stimulate the solar cooling sector for small and medium power size was identified.

Within this context, a new task on new generation PV and solar thermal driven cooling and heating systems is initiated by the IEA. SHC, task 53, which is focused on solar driven systems for both cooling (ambient and food conservation) and heating (ambient and domestic hot water).

One of the main objectives of this task is the analyse of the interest of new generation (PV or solar thermally driven) solar cooling & heating concepts systems for buildings in all climates and the selection of the best solutions which lead to highly reliable, durable, efficient and robust solar cooling and heating (ambient +DHW) systems. Another major objective is the contribution to market entry of the new generation PV or solar thermally driven cooling technology and the identification of the most promising market areas in terms of cost competitiveness and value of electricity.

To achieve these objectives, a major challenge is the energy management on building neighbourhood, district and urban level.

This deliverable presents a complete state of the art of the energy storage, both thermal and electrical, for solar driven cooling and heating systems. The documents is divided into two major parts: thermal storage and electrical storage. After a global overview, mature and in development technologies applied to solar heating and cooling systems are investigated and presented. Numerical simulations are performed afterwards to identify the most suitable storage method/size for different climates and types of buildings. Finally, a pre-selection of a storage method depending on the energy demand and other parameters can be realized.

1 Storage for solar heating and cooling systems

1.1. Objectives of storage for solar heating and cooling systems

The general objectives of storage in solar heating and cooling system are to exploit the maximum energy potential and to optimize self-consumption if the primary source of energy is solar electricity. As decentralized electricity production is one of the main challenges of electricity grids, self-consumption[1] will become one of the major aspects of electricity self-production.

The specific objectives of a storage facility depend on the characteristic of the solar heating and cooling system. It can involve a daily storage or a seasonal storage, thermal or electricity storage and small or large-scale storage.

1.2. Control strategy of storage

To take full advantage of a solar heating or cooling system, including thermal or electricity storage, an extensive optimization of the control strategy of energy systems in buildings is required. The use of an artificial intelligence to optimize energy production, minimize electric grid use, minimize energy consumption and optimize solar heating and storage systems is an essential factor for efficient energy storage. Thus, it allows a decentralized energy production on building, on district and neighbourhood level, a better solar integration, solar use and a significant reduction of CO_2.

One example is the company Cosseco that has developed the product Solarline, combining photovoltaic panels and heat pump. Solarline is based on its own new generation and smart control. It was created on an economic and ecological concept: to self-consume the maximum of the electricity produced by solar photovoltaic (PV) panels. Cosseco has developed an unique control system to achieve this goal. It allows using every single kWh of solar electricity. Moreover, the system uses the storage capacity of water tanks to balance the daily fluctuating electricity generated by the photovoltaic system. In water tanks, hot water can be stored as well as cold water for cooling during summer. Another important point is the modulation of the heat pump power. The power is set to have the best performance and to consume the entire photovoltaic production. It uses a power modulating heat pump system made up of a heat pump and heating and air conditioning system that improves the performance at part loads, and lowers the operating costs by heat storage and/or modulating the output of the system to meet the heating and cooling needs of the building.

Another key point for the control strategy is the weather forecast, which allows the anticipation of the temperature trend and the adaptation for the heating or cooling demand accordingly allowing both energy savings and an improvement of the thermal comfort.

[1] In a building equipped with roof-top PV plant the energy self-consumption is defined and the ration between the energy provided by the PV and the whole energy required by the building it-self.

1.3. Criteria to determine the most relevant storage

The criteria to determine the most relevant storage methods for solar cooling or heating system are the following:

- **Type of energy storage:** As the energy used for heating and cooling can be thermal or electrical, storage methods for both types of energy being described below. Moreover, energy can be stored in chemical form. The water pump-storage is not determined suitable for solar heating or cooling systems. This storage method is more appropriate at grid level than at a heating or cooling system.
- **Time scale of storage**: For solar heating and cooling systems, the storage timespan starts from hourly and ends with seasonal intervals. Therefore, the storage methods covers a wide range. In case of an off-grid system, the small variations of the PV production can be compensated thanks to a small-scale storage. Solar heating district integrating seasonal storage is out of the scope of this Task.
- **Storage capacity:** The storage method retained for solar heating and cooling systems ranges from very low energy storage capacity, for an off-grid system for example, to very large storage capacity, for seasonal storage.
- **Life duration:** The life duration of the storage facility is an important information since it allows for evaluating its economic sustainability.
- **Efficiency:** The overall efficiency of the storage system needs to be in balance with the cost of the energy production.
- **Cost:** To estimate the cost of a storage facility, it is necessary that the considered storage system is, or will soon be on the market. If the product is on the market, the cost need to be compared with the gain achieved with the chosen storage.

1.4. Storage methods for solar heating and cooling system

The following paragraphs describe the relevant storage methods chosen to be combined with solar heating and cooling systems up to 100 kW. The short description is taken from the technology roadmap report on energy storage of the International Energy Agency [3].

Batteries use chemical reactions with two or more electrochemical cells to enable the flow of electrons. Examples include lithium-based batteries (ex: lithium-ion, lithium polymer), sodium sulphur, and lead-acid batteries.

Supercapacitors store energy in large electrostatic fields between two conductive plates, which are separated by a small distance. Electricity can be quickly stored and released using this technology in order to produce short bursts of power.

Chemical-hydrogen storage uses hydrogen as an energy carrier to store electricity, for example through electrolysis. Electricity is converted, stored, and then re-converted into the desired end-use form (e.g. electricity, heat, or liquid fuel).

Thermochemical storage uses reversible chemical reactions to store thermal energy in the form of chemical compounds. This energy can be discharged at different temperatures, dependent on the properties of the thermochemical reaction.

Underground thermal energy storage (UTES) systems pump heated or cooled water underground for later use as a heating or cooling resource. These systems include aquifer and borehole thermal energy storage systems, where this water is pumped into (and out of) either an existing aquifers or man-made boreholes.

Solid media storage systems store energy in a solid material for later use in heating or cooling. It is the building mass storage. In many countries, electric heaters include solid media storage (e.g. bricks or concrete) to assist in regulating heat demand.

Phase change material is a form of latent heat storage, where energy is stored in a material that undergoes a phase change as it stores and releases energy. A phase change refers to transition of a medium between solid, liquid, and gas states. This transition can occur in either direction (i.e. from a liquid to a solid or vice versa), depending on if energy is being stored or released.

Hot- and cold-water storage in tanks can be used to meet heating or cooling demand. A common example of hot water storage can be found in domestic hot water heaters, which frequently include storage in the form of insulated water tanks.

The

Table 1 shows the different selected storage methods and their characteristics. The

Table 2 presents the advantages, the disadvantages and the domain of application of each storage method. Different cases of application of each type of storage methods are detailed in the

Table 3.

Table 1. Characteristics of the selected storage methods

Technology	*Output*	*Efficiency (%)*	*Initial investment cost (USD/kW)*	*Time scale storage*	*Temperature storage*
Batteries	Electricity	75 - 95	300 – 3’500	Short-term storage	-
Chemical - hydrogen storage	Electricity	22 - 50	500 - 750	Long-term storage	-
Supercapacitors	Electricity	90 - 95	130 - 515	Short-term storage	-
Thermochemical	Thermal	80 - 99	1’000 – 3’000	Long-term storage	Low, medium, and high-temperature applications
Underground thermal energy storage	Thermal	50 - 90	3’400 - 4’500	Long-term storage	Medium temperature applications
Solid media storage	Thermal	50 - 90	500 - 3’000	Mid-term storage	Medium temperature applications
Ice / slurry ice storage	Thermal	75 - 90	6’000 - 15’000	Mid-term storage	Low-temperature applications
Hot water storage (residential)	Thermal	50 - 90	-	Mid-term storage	Medium temperature applications
Cold-water storage	Thermal	50 - 90	300 - 600	Mid-term storage	Low-temperature applications

Table 2. Advantages and disadvantages of the storage methods

Technology	**Advantage**	**Disadvantage**	**Domain of application**
Batteries	Cost	Life duration, storage capacity	Off-grid building
Chemical- hydrogen storage	Very low losses, high energy density	Cost, technically complex	Building with a high solar fraction
Supercapacitors	Very high power (dis)charge capacity	Cost, storage capacity	
Thermochemical	Very low losses, high energy density	Cost, technically complex	Building with a high solar fraction
Underground thermal energy storage	Costs, high storage capacity	Depending on geological properties, authorisation needed, losses	Seasonal storage for district heating
Solid media storage	Energy storage in the building structure	Cost, energy capacity storage	All the buildings with a concrete structure.
Ice and slurry ice storage	High energy density	Technically complex	Cooling with a large variation between night and day
Hot water tank storage (residential)	Low cost, technically simple	Losses	Standard for thermal storage
Cold-water tank storage	Low cost, technically simple	Losses	Standard for thermal storage

Table 3. Examples of products for each storage method

Technology	*Product*	*Initial investment cost*	*Storage capacity*	*Volume (m^3)*	*Temperature storage*
Underground thermal energy storage	ATES Rostock, D	171’600€	~ 200 MWh	20’000	15-50°C
Underground thermal energy storage	BTES Crailsheim, D	590’000€	~ 350 MWh	37’500	20-50°C
Batteries	BPT-S5 Hybrid, Bosch	400-1000 €/kWh	13.2 kWh	0.7 m^3	-
Chemical- hydrogen storage	Acta Power / McPhy	75 € / MWh producted	40 kWh	30 m^3	-
Supercapacitors	Nesscap Ultracapicitor	> 1000 €/kWh	0.14 kWh	0.1 m^3	-
Phase change material	BioPCmat™ M91	50.5 $/$m^2$	0.287 kWh	1 m^2	~ 23°C
Ice storage	ICEBAT, Fafco SA		289 kWh	8.64 m^3	0°C
Hot and cold water storage	Solarline, Cosseco	9’000 CHF	110 kWh	2 m^3	10-70°C

The storage methods are detailed in the following sections.

1.4.1. Electrochemical Battery

Last 5 years, electrochemical batteries have seen a large deployment for two main types of applications: i) provide ancillary services to the power-grid (such as frequency and voltage control, peak shaving, load levelling and so on) and ii) increase the energy self-consumption of a building equipped with PV power plant (for heating or cooling systems, electrochemical batteries are not commonly used).

The second application is actually the main interesting but it is important to underline that the economic profitability of the electrochemical battery depends strongly on the selling price of the electricity (4-15 ct $/kWh), the retail electricity price (15-35 ct $/kWh) and, last but not least the ageing of the battery itself (2000-25000 cycles).

It is worth observing that for large decentralized energy storage, namely from 100 kWh up to several MWh, the electrochemical battery cannot economically compete with large-scale pumped-storage hydroelectricity.

For more information, see chapter 6.

1.4.2. Ultracapacitor

The technology of the ultra/supercapacitor is well defined and it is possible to use it for hybrid energy storage systems [5]. This specific application is correlated to their very low energy-density of (0.1-0.5 Wh/kg) and very high power-density (10-15 kW/kg). In this system, an ultracapacitor allows for absorbing the fast power variation of the electricity consumption. Ultracapacitors could also compensate fast variation of PV production due to clouds’ shadows.

1.4.3. Thermochemical storage

This technology is mainly used to store energy produced by concentrating solar power plants. It allows heating up water to a high temperature. It is the most promising technology for seasonal storage thanks to very low energy losses in time, high energy density and higher efficiency than water based seasonal storage. However, the application to seasonal storage for heating or cooling solar system is still under development and therefore no well-established product is on the market. Despite the actual research state, this technology is a major storage method to achieve the total energy independence to the grid.

1.4.4. Hydrogen storage

Hydrogen storage allows to store PV production with no losses in time, but has a low efficiency (maximum of 50%). Therefore, this technology is only viable for seasonal storage and if the solar production is higher than the consumption needs during the year, due to the low overall efficiency. Several integrated systems (hydrogen production, storage and consumption) are on the market. They target mainly the off-grid system, which needs to be 100% energy self-sufficient. The achievement of a 100% self-sufficient system is limited by the cost.

1.4.5. Underground thermal energy storage

Underground thermal energy storage is commonly used for seasonal heat storage on large scale systems. Since the losses depend on the storage volume, a minimal size of the storage system is necessary to reach an acceptable efficiency. Therefore, UTES is mostly used in district heating grids. Both systems can also be used for cooling applications during summer.

For example, an aquifer thermal energy storage in Berlin (Germany) uses two separated aquifers. The first one is located in a depth of 60 m under the ground surface and is used to store ambient cold in winter, to cool the rooms of the parliament building during summer. In a depth of 300 m, there is a second aquifer to store waste heat arising from a from a biodiesel-driven cogeneration plant and reuse it for space heating later on. However, a similar effect can be achieved by using one aquifer, if the temperature level of the cold well is low enough [8].

1.4.6. Solid media storage

The storage in solid media can be commonly used in the buildings with concrete structure. The storage can be optimized with an active sub-slab heating system. This storage method can complement another storage method.

An example of a solid media storage in combination with another storage type is a packed bed of rocks combined with PCM [7]. The system was designed to store solar energy. The aim of the PCM in the system is to stabilize the storage output temperature.

1.4.7. Phase change material (PCM)

The phase change materials have a high energy density. There are several applications of this storage method: it allows increasing the energy density of water tanks or increasing the heat capacity of buildings by integrating PCM in ceiling or walls. The second application increases the thermal inertia and therefore the temperature variation in the building. Thus, the utilization of PCM in the building structure increases the thermal inertia during heating and cooling periods. Therefore, the PCM application is interesting for buildings with high direct solar heat gain.

Several PCM products are on the market. One example is the product BioPCM of the company Phase Change Energy Solutions. It provides encapsulate PCM in plastic rolls. These materials are available for several melting temperatures and are inserted in the ceilings or walls.

Many research project are currently ongoing regarding the PCM storage. An example is CSIRO, Australia, which is working on design, development and testing of a storage system suitable for high temperature (200 – 250°C) solar cooling applications. This system will incorporate solar resource forecasting algorithms in the control strategy to maximize system benefits.

Research efforts are focused on the following tasks

- Model based (validated) comparison of suitable storage material and strategy for high temperature solar cooling applications. Sensible and latent heat materials have been evaluated as a part of this effort for a typical application such as office air conditioning for Australian climates (typical results see Figure 1).
- Design, install and commissioning of a test rig for studying high temperature storage systems in a solar air conditioning facility. Tests have been carried out using single axis tracking Fresnel collectors as the heat source, thermal oil as the storage material and a simulated chiller that uses heat input similar to a double effect chiller (180°C),
- Model predictive Control (MPC) approaches have been proposed as an effective way to improve the overall system performance. In the present work, we investigate the benefits of MPC in a high temperature solar cooling system with thermal storage providing cooling to a commercial building. This control utilizes weather forecast information to provide future control strategies that minimize the usage of auxiliary heat source. Results show the controller is able to reduce backup usage through enhancing the solar collector yield and reducing the tank heat losses) (typical facility see Figure 2)

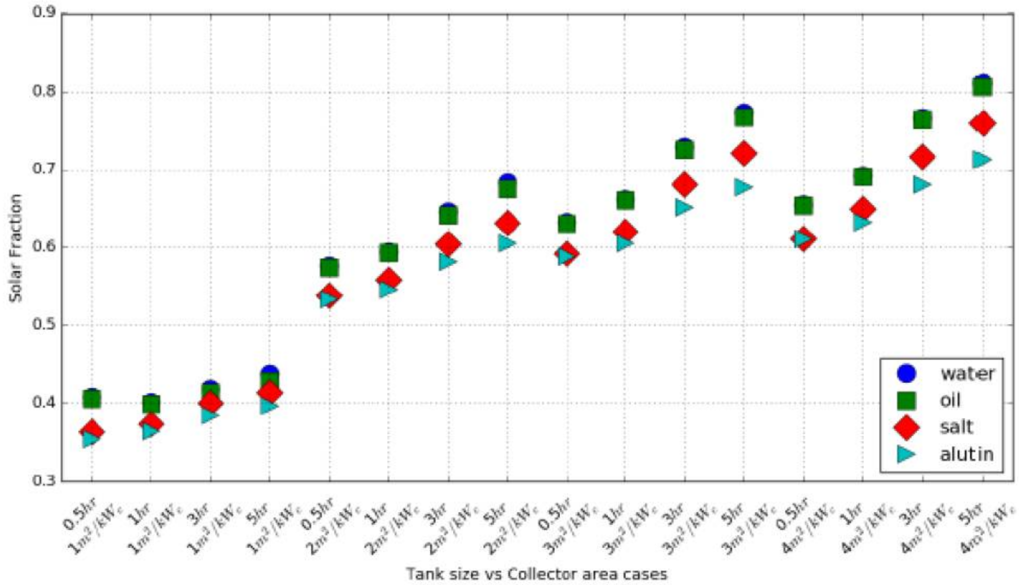


Figure 1. Storage material benefits for a solar cooling system (application office building in Sydney)

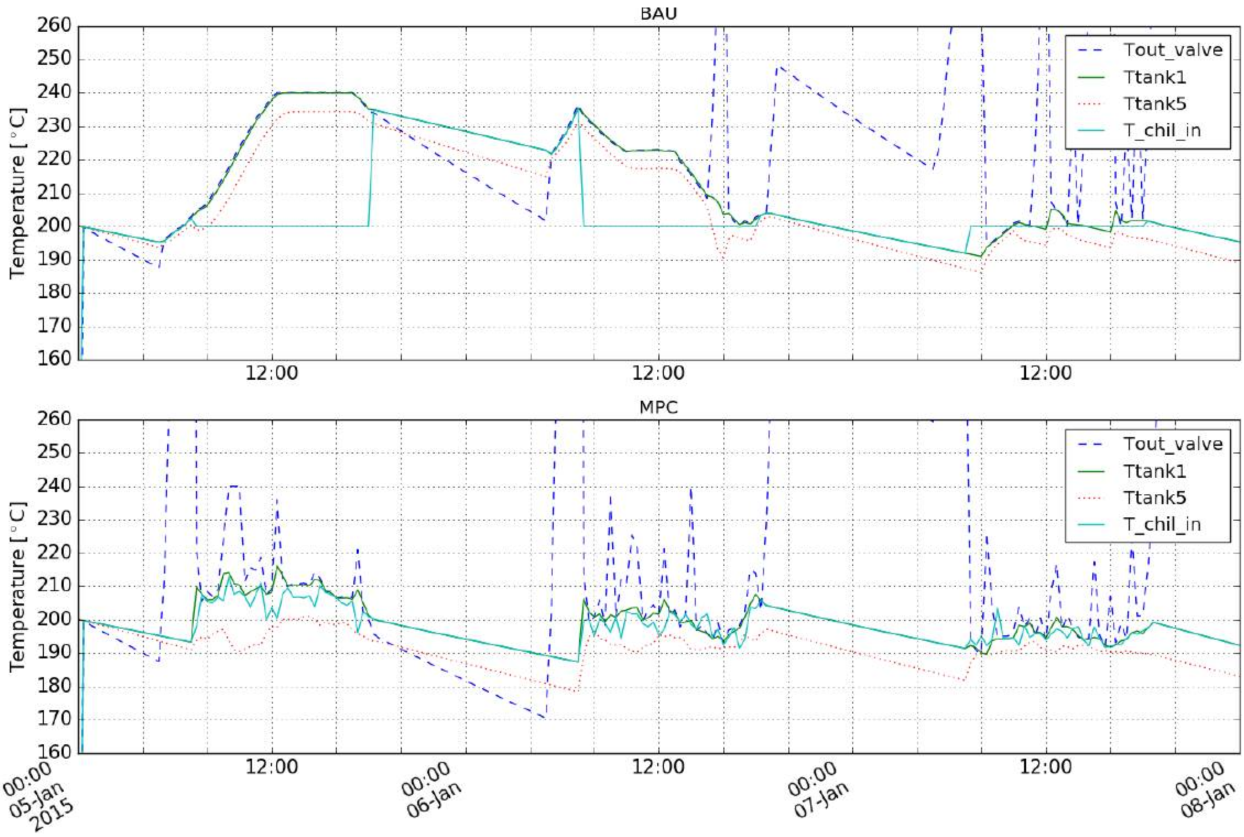


Figure 2. Comparison of system temperature state between standard controller (BAU) and MPC for a solar cooling system

Another interesting project ongoing leaded by the Bavarian Center for Applied Energy Research (ZAE Bayern) is the quantification of the best temperature level (melting temperature) of the PCM-material for the integration into the Cooling-Circuit of a VRF-installation.

The project approach is to implement a PCM-based storage directly to the refrigerant cycle of an air/air based VRF (Variable Refrigerant Flow) system. Especially when these systems are PV driven it is a mandatory need to store energy due to the delay between the peak of PV- production and cooling demand. Compared to sensible thermal storages the nearly constant temperature of PCM during phase change can cause significant efficiency gains in the system due to less exergetic losses. Depending on the application, a wide range of melting temperatures of the PCM can be considered. It is necessary to figure out materials whose melting temperatures are well adapted to the refrigerant cycle of the VRF systems.

To specify the most promising temperature ranges for the integration of PV-production, transient simulations of thermal load and PV-production for a specific office building in the south of Germany have been made in TRNSYS. To simulate the possible thermal supply of the PV-driven system the model was also fed by the ambient temperature- and part load dependent data of the EER/COP of the VRF-system.

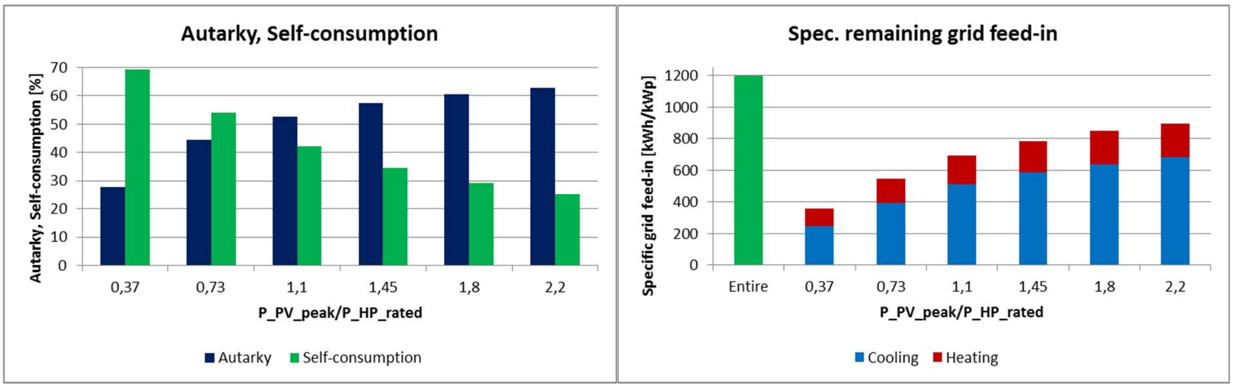


Figure 3. Autarky and self-consumption of the PVHP system (left) and specific remaining grid feed-in after self-consumption (right). The installed PV peak power is varied. PV peak power is related to the rated electrical power of the heat pump

Figure 3 shows one result of the modelling phase. On the left-hand side there is shown autarky and self-consumption of the PVHP system for different PV peak power installations. The installed PV power is rated to the nominal electrical power of the heat pump. For oversized PV-installation you can see that autarky is reaching saturation while self–consumption is still decreasing. That leads to the opposite of the required goal, stress reduction to the grid by minimizing grid feed-in. It could then only be compensated by oversized, non-economic storages. On the right-hand side of the Figure 3, the specific remaining grid feed-in is divided into dominant cooling and dominant heating mode of the system. The major part of remaining grid feed-in occurs in cooling mode. By taking a closer look at remaining feed-in for a PV-power range > 50% of the installed peak-power the ratio is even getting more to the cooling side.

The possible size of VRF-systems with up to 60 or more indoor units per outdoor unit and partly long wiring distances of the refrigerant circuit leads to circumstances where the level of evaporating and condensing is nearly fixed in very tight temperature ranges. The following log(p)/h diagrams respect that with the shown isotherms for $T_{Condens}$ and T_{Evap}.

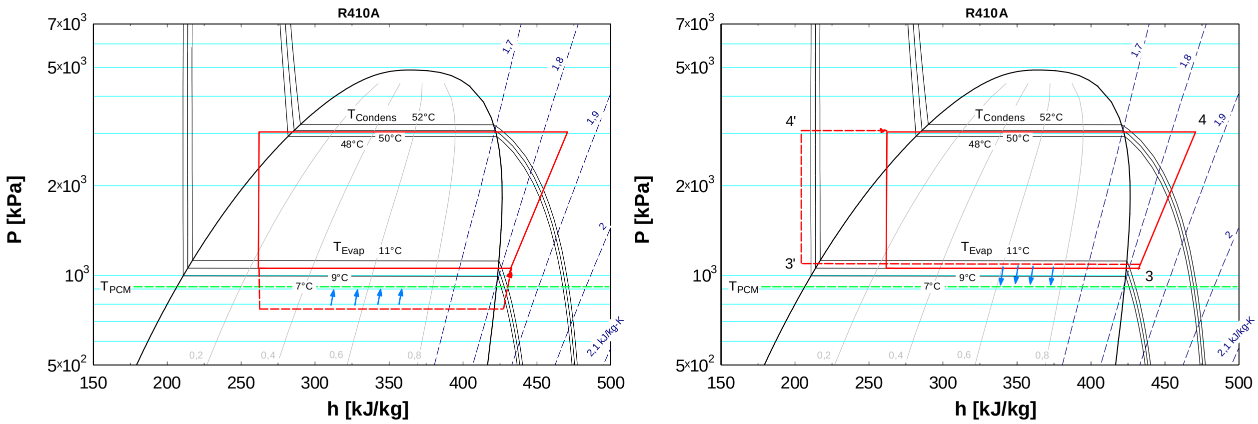


Figure 4. Log(p)/h diagram PCM storage as central cold storage in case of charge (left) and discharge (right)

Figure 4 shows the cooling circuit when the storage is used as central cold storage. The storage is implemented like an additional indoor unit to the system. The evaporating temperature T_{Evap} of the entire VRF systems is selectable between 7 °C to 11 °C. The melting temperature of the storage (green line) needs to be lower than the evaporating temperature of the system. In times of PV-overproduction, the storage is charged through a second compressor (diagram on the left hand side). The additional compressor pulls down the evaporating temperature just for the storage part while the remaining system keeps working on the higher evaporating level. Especially for installations with a large number of indoor units, this additional pull down is favourable. Only the refrigerant loading the storage needs to overcome a higher temperature lift. That leads to low efficiency losses through charging. Discharging is shown on the diagram on the right-hand side of the Figure 4. A charged storage on a lower temperature level as the common evaporating level is able to exhaust part of the evaporated refrigerant and condense it. Part of the refrigerant can now be lifted in liquid phase to the high-pressure level (3´-> 4´). The main compressor can be relieved significantly when it is needed to adapt a high thermal load to decreasing PV-yield.

To determinate the best melting temperature ranges for the possible configurations the cooling circuits had been modelled in EES (Engineering Equation Solver).

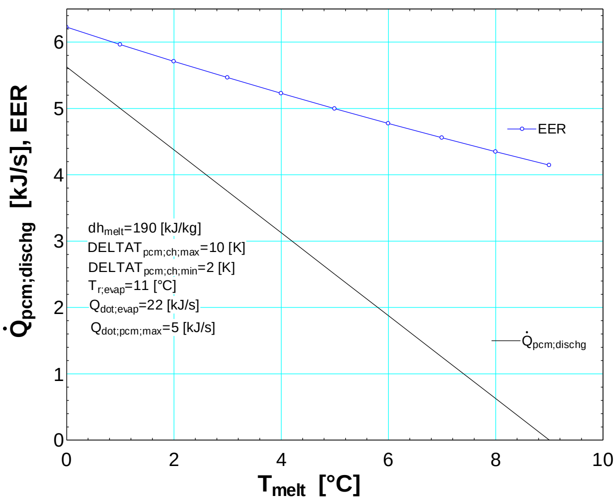


Figure 5. EER development and transferable power capacity in case of discharge for different melting temperatures of the PCM

Figure 5 shows different melting temperatures of the storage and the development of the EER and the possible discharge power capacity for the above described implementation. The VRF system has a nominal cooling capacity of 22 kW at an evaporating level of 11 °C. The storage can reach a power capacity of maximum 5 kW and uses a PCM material with a specific enthalpy of 190 kJ/kg. Figure 5 shows the development of the system EER at the nominal operating point (nominal EER = 4.11). There is a nearly linear increase of the EER the lower the phase change temperature gets. A higher difference between common evaporating level and melting temperature leads to a higher natural pressure difference. Therefore, the storage is able to exhaust more vaporised refrigerant and to relieve the compressor more in case of discharge. Furthermore, the black line represents the possible discharge power the storage can achieve. Using melting temperatures above 5 °C it is no more possible to transfer sufficient discharge power from the storage to the system. Due to the results, a usable melting temperature for that configuration is placed between 0 °C to maximum 5 °C.

Another possible implementation is to use the storage as additional subcooler in the refrigerant cycle. Figure 6 shows the cooling circuit in case of charge (left) and discharge (right).

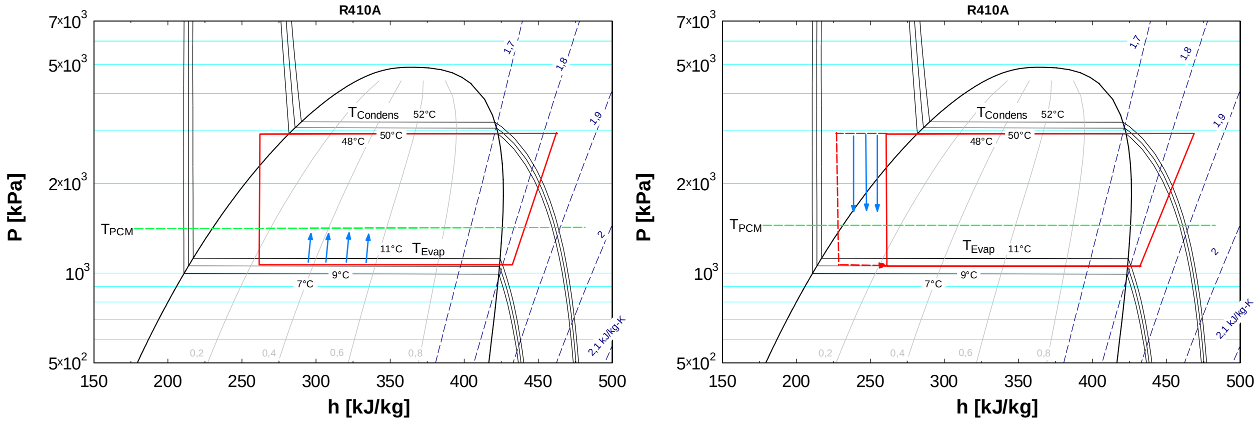


Figure 6. PCM storage used as additional subcooler in case of discharge (right) or charging on the common evaporating level of the system (left)

On the left-hand side, you can see the charging of the storage using PV surplus energy. The storage is now charged on the common evaporating level of the system. Therefore, the phase change temperature (green line) has to be above this level. While charging, the storage is also connected to the system like an additional indoor unit. Using the common evaporating level there are no EER losses expected while charging. The storage works as additional load. Due to a higher part load ratio, positive effects on the EER while charging are expected. On the right diagram, you can see the discharge of the storage. When thermal load exceeds solar supply, the liquid refrigerant is lead through the storage and subcools near the melting temperature of the chosen material. There are two benefits to achieve:

- A higher usable enthalpy difference for cooling compared to conventional subcooling.
- Reaching sufficient subcooling by the storage you can substitute the conventional subcooler. Those systems usually subcool the refrigerant by evaporating a part of the condensed refrigerant to low pressure level. This part of the refrigerant is lost for the energy conversion but has to be transported by the compressor.

Both benefits lead to an increase of the EER for the same thermal load like in the conventional system. This gives the possibility to lower electrical demand when it is appropriate.

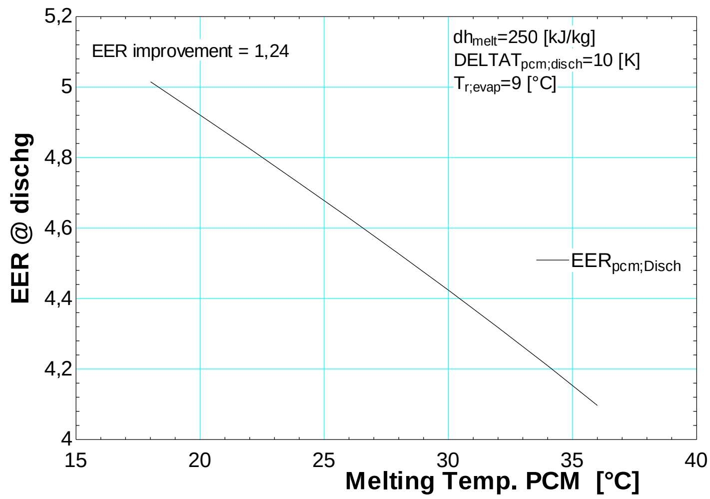


Figure 7. EER improvement in case of discharge for different melting temperatures of the PCM (storage working as subcooler)

Figure 7 shows the EER improvement of the system varying the melting temperature of the PCM-storage. The system works on its nominal conditions at an evaporating level of 9 °C. The PCM material has a specific enthalpy of 250 kJ/kg. The lower subcooling gets (due to a lower melting temperature) the more EER improvement can be reached. On the other hand, a sufficient temperature difference between melting temperature and evaporating temperature is ensured in case of charge. Taking both into account, the ideal melting temperature range for this implementation is between 16 °C and 21 °C.

1.4.8. Ice storage

Ice storages use water as phase change material (PCM) to store energy for up to one month and benefit of the latent heat to increase the storage capacity. In combination with a heat pump, the storage can be used as heat source and recharged by solar thermal panels. Since the storage temperature is low (0°C), the ice storage can be used directly for air conditioning or other cooling applications. A fully functional system reaches efficiencies on the level of a heat pump with boreholes or even higher. Since this technology is rather new and still under development, there are even better properties to be expected for future systems. Difficulties lie within the optimal dimension of the components and the complex control of the system.

The technology is used for midterm storage. Up to now, there are just three standard solutions available in Switzerland with a heating power output in between 6 and 17kW, which are used for rather small buildings. Nevertheless, there are also individual constructions of larger scale. For example, a residential complex in Geneva that was renovated in 2012 and in the same time equipped with a new heating system. The solar energy yield of 1’680 m^2 solar thermal panels is stored in two ice storage tanks of 30 m^3 each. A heat pump of 130 kW power output uses the stored energy as heat source [9]. Much more known is the use of ice storage for cooling applications only. Systems like this are commonly used for air conditioning or industrial cooling.

1.4.9. Hot and cold water tank

This technology is widely spread and standard for solar heating and cooling systems. A water tank is optimal to store thermal energy up to several days. Some systems for solar seasonal storage are existing, but due to the losses, the systems are not viable economically.

An example is a storage facility designed for a system coupling heat pump and photovoltaic panels. Energy is stored in the water tank and in the building structure. The water tanks are used for the domestic hot water and the heating system. Buffer tanks for the heating system store cold water during the hot period and hot water during the rest of the year. This system allows optimizing the self-consumption of a photovoltaic production. This storage method is particularly for buildings with cooling needs during the summer and heating the rest of the time. The company Cosseco has developed the smart regulation for this type of facility. The product is called Solarline [4].

2. Storage optimization

Storage plays a major role in a solar driven renewable energy system for heating and cooling. Thus, the storage method needs to be correctly chosen and storage capacity sized. The storage is often composed of a combination of different storage methods as it is presented above.

The two main parameters to consider in order to optimize and to determine the storage capacity of a solar heating or cooling system are a) the self-consumption and the b) profitability. The optimization of storage volume depends directly on the desired energy saved thanks to the storage. Moreover, the amount of saved energy is influenced by of the price of auxiliary energy and its evolution.

Therefore, the profitability of a storage method depends strongly on the local conditions like weather, investment costs, financial subventions and energy prices.

CSIRO, Australia, has developed an approach for evaluating the benefits of latent heat storage and sensible heat storage in the context of high temperature (200 – 250^{o}C) solar cooling applications. More details of their approach is provided in section 3.

3. Choice of the storage type and sizing

Not only the cost but also the efficiency of a solar driven thermal storage system depends on the dimensions of its components. For example, a small storage reduces the solar fraction of the system because it cannot store enough energy to supply the system during times of low production. Similar, the oversized storage is not good, since it will take a lot of energy to supply it in order to reach an appropriate temperature level.

Similar to the planning process of every heating system, in first place, the energy consumption of the building or district heating grid has to be evaluated. This value depends on the space and water volume to be heated, as well as on the insulation of the building, its location and the weather conditions.

Two typical examples for storage evaluation are provided below. Section 3.1, 3.2**Erreur ! Source du renvoi introuvable.** is about storage choices for European climatic conditions and sections 4.3 is about storage selection for a solar cooling application in Australia.

3.1. Choice of storage type

As a next step after evaluating the energy demands of the different building types, the storage type should be chosen. Therefore, the following tables will give an overview, which storage methods could be suitable depending on the building type and its location. The energy needs of different buildings in different locations within the three defined climatic zones were simulated in Polysun 7.2[2], which uses weather data from a software called Meteonorm [10] [11]. The locations are shown as red points on the map below.

3.1.10. Climatic zones

[2] Polysun 7.2, simulation software used to design of solar thermal, heat pump and photovoltaic systems as well as combined systems

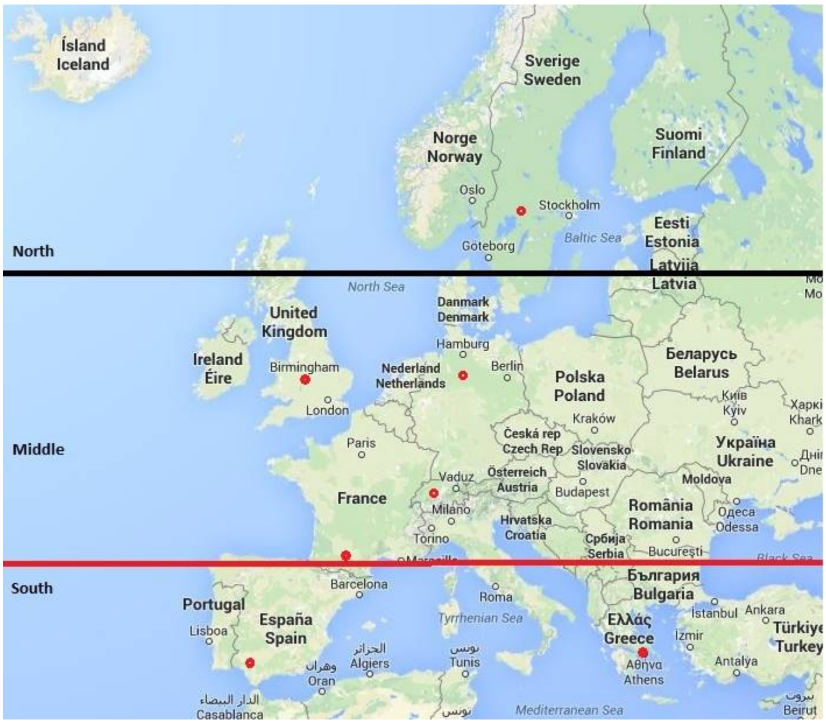


Figure 8. Targeted climate regions in Europe

Northern climatic zone (Iceland, Norway, Sweden, Finland)

Because of long winters, a lot of energy is used for heating purposes. Since the temperature even in summertime is not high, usually cooling is not necessary for residential buildings.

Middle climatic zone (United Kingdom, France, Germany, Switzerland, Austria…)

In the middle zone, temperatures can reach up to 30-35°C in summer. Some buildings like hotels or offices use air conditions, but the main energy consumption still lies within hot water and space heating during winter.

Southern climatic zone (Portugal, Spain, southern Italy, Greece…)

Hot summers require a lot of energy for air conditioning in the southern zone. Since solar energy can also be used in winter, the need for long-term storage is lower.

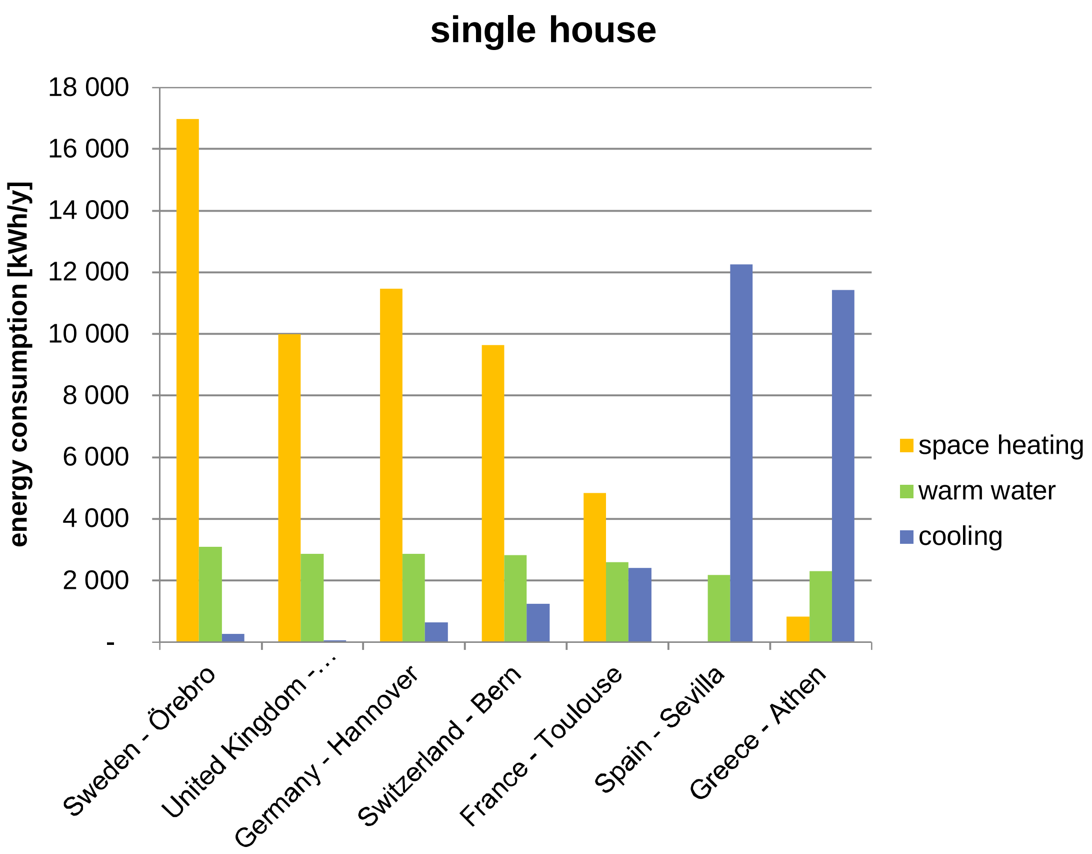
3.1.11. Building types

Single house

Building description		
Heated surface	**[m²]**	**200**
Insulation (U value)	**[W/(m² K)]**	**0.35**
Surface per person [1]	[m²/p]	60
Number of persons	[-]	3.3
Daily presence[1]	[h]	12
Heating power per person [1]	[W]	70
Internal heat source due to persons	**[W/m²]**	**0.58**
Electricity consumption [1]	[MJ/(y·m²)]	80
Factor heat production from electricity consumption [1]	[-]	0.7
Internal heat source due to installations	**[W/m²]**	**1.78**
Energy consumption for hot water [1]	[MJ/(y·m²)]	50
Hot water daily consumption per person	[l/(p·d)]	50
Daily hot water consumption total	**[l/d]**	**167**

[1] parameters according to SIA norm 380/1 [10]

Values written bold are calculated from the given values according to the norm and used in Polysun as building parameters.

Consumption profile and storage properties


This diagram contains the results of a Polysun simulation depending on the weather data from Meteonorm, which is included in Polysun, and common building parameters of a single house according to the SIA norm 380/1. [10] [11]

	Cooling	Space heating	Hot water
North **(Sweden - Örebro)**	Very low need, ambient temperature low enough	Low need because of small heated surface	Low need, not many persons
Energy consumption [kWh]	258	16’968	3’076
Suitable storage Method	• Hot water tank as short- and midterm storage • The cooling needs can be covered by solid media storage realized with concrete walls and night ventilation. •		
	Cooling	Space heat	Hot water

Middle (Bern – Switzerland)	Very low need, ambient temperature low enough	Low need because of small heated surface	Low need, not many persons
Energy consumption [kWh]	1’239	9’630	2’803
Suitable storage Method	• Hot water tank as short- and midterm storage • The cooling needs can be covered by solid media storage realized with concrete walls or even PCM integrated in the concrete.		
South (Spain – Seville)	Medium need to keep temperature below 24°C	Very low need to keep ambient temperature usually high enough	Low need, not many persons
Energy consumption [kWh]	12’247	0	2’164
Suitable storage Method	• Hot water Tank for hot water needs, Ice storage would be a good but expensive solution to cover cooling needs		

The following table shows an estimation of the most economical storage technology for a single house depending on its location.

+ main storage (long term)
o additional storage (short term)

	Single house – northern climate zone	Single house – middle climate zone	Single house – southern climate zone
BTES			
ATES			
Pit storage	+	+	
Solid media/ building mass	o	o	o
PCM	o	o	o
Ice storage			+
Hot and cold water tank	++	++	++

This table can only be used as estimation, the best storage method for an individual building and location has to be evaluated from case to case.

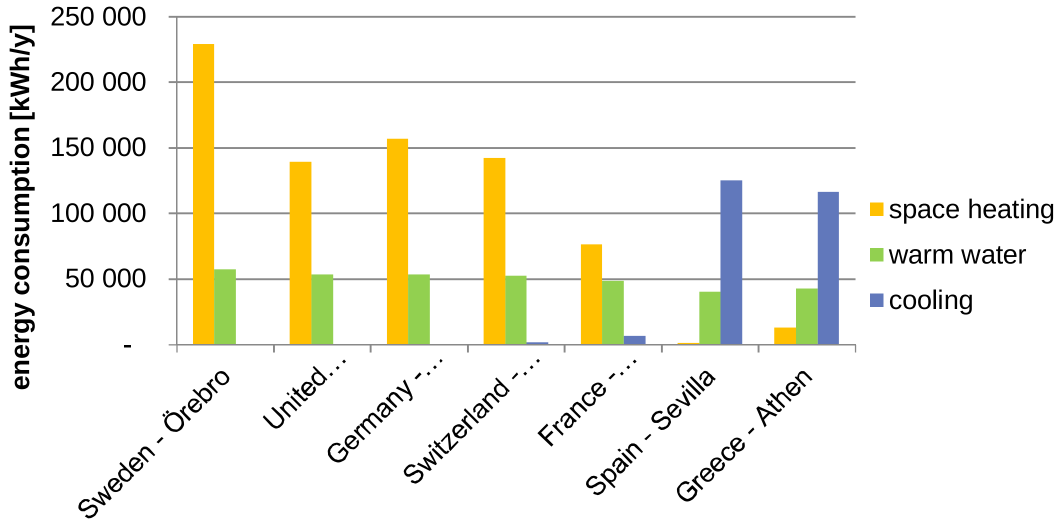
Multi-family residential

Building description		
Heated surface	**[m^2]**	**2500**
Insulation (U value)	**[W/(m^2 K)]**	**0.35**
Surface per person [1]	[m^2/p]	40
Number of persons	[-]	62.5
Daily presence[1]	[h]	12
Heating power per person [1]	[W]	70
Internal heat source due to persons	**[W/m^2]**	**0.88**
Electricity consumption [1]	[MJ/(y·m^2)]	100
Factor heat production from electricity consumption [1]	[-]	0.7
Internal heat source due to installations	**[W/m^2]**	**2.22**
Energy consumption for hot water [1]	[MJ/(y·m^2)]	75
Hot water daily consumption per person	[l/(p·d)]	50
Daily hot water consumption total	**[l/d]**	**3'125**

[1] parameters according to SIA norm 380/1 [10]

Values written bold are calculated from the given values according to the norm and used in Polysun as building parameters

Consumption profile and storage properties



The diagram above contains the results of a Polysun simulation depending on the weather data from Meteonorm, which is included in Polysun, and common building parameters of a multi-family residential according to the SIA norm 380/1. [10] [11]

	Cooling	Space heating	Hot water
North (Sweden - Örebro)	No need, ambient temperature low enough	High need	Medium need
Energy consumption [kWh]	0	228’817	57’220
Suitable storage Method	• UTES or pit storage in combination with a hot water tank. • The cooling needs can be covered by solid media storage realized with concrete walls.		
Middle (Bern – Switzerland)	Very low need, ambient temperature low enough	Medium needs	Medium needs
Energy consumption [kWh]	1’336	126’136	69’817
Suitable storage Method	• UTES or pit storage in combination with hot water tank. • The cooling needs can be covered by solid media storage realized with concrete walls or even PCM integrated in the concrete		
South (Spain – Seville)	High need, to keep temperature below 24°C	Very low need, ambient temperature usually high enough	Medium need
Energy consumption [kWh]	124’837	919	40’272
Suitable storage Method	Ice storage for cooling in combination with hot water tank.		

The following table shows an estimation of the most economical storage technology for an apartment block depending on its location.

\+ main storage (long term)
o additional storage (short term)

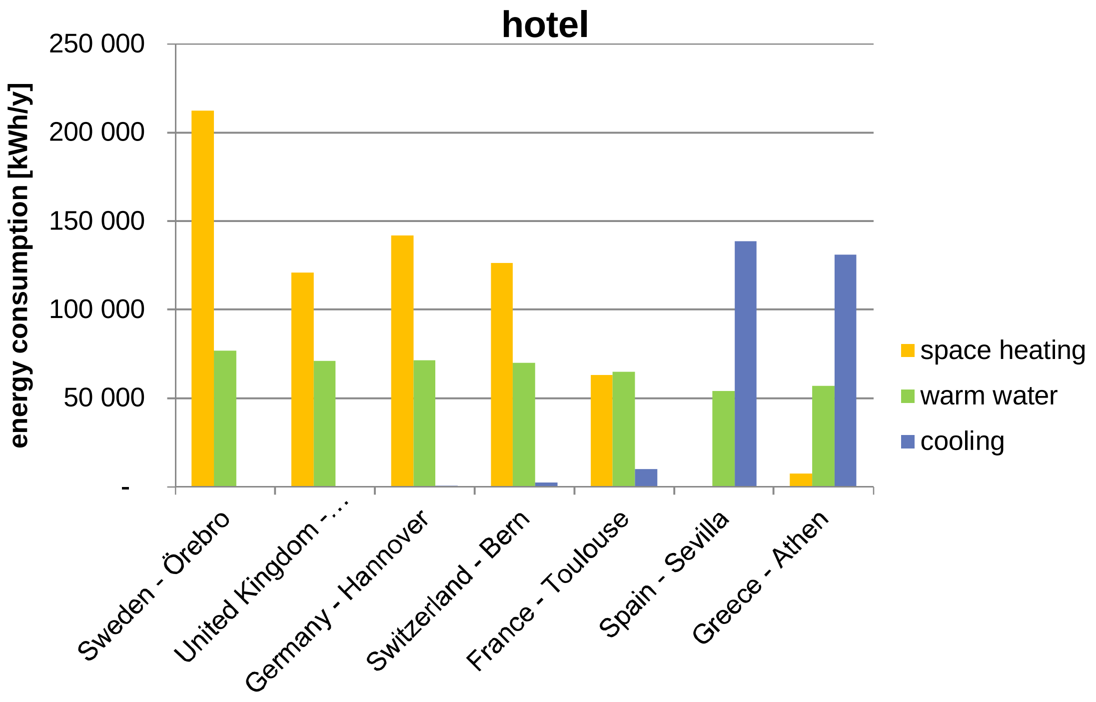
	Multi-family residential – northern climate zone	Multi-family residential – middle climate zone	Multi-family residential – southern climate zone
BTES	+	+	
ATES	+	+	
Pit storage	+	+	+
Solid media	o	o	o
PCM	o	o	o
Ice storage			++
Hot and cold water tank	+ / o	+ / o	+ / o

The previous table can only be used as estimation, the best storage method for an individual building and location has to be evaluated from case to case.

Hotel

Building description		
Heated surface	**[m²]**	**2500**
Insulation (U value)	**[W/(m² K)]**	**0.35**
Surface per person [1]	[m²/p]	30
Number of persons	[-]	83.3
Daily presence[1]	[h]	12
Heating power per person [1]	[W]	70
Internal heat source due to persons	**[W/m²]**	**1.17**
Electricity consumption [1]	[MJ/(y·m²)]	100
Factor heat production from electricity consumption [1]	[-]	0.7
Internal heat source due to installations	**[W/m²]**	**2.22**
Energy consumption for hot water [1]	[MJ/(y·m²)]	100
Hot water daily consumption per person	[l/(p·d)]	50
Daily hot water consumption total	**[l/d]**	**4’167**
[1] parameters according to SIA norm 380/1 [10]		

Consumption profile and storage properties



This diagram contains the results of a Polysun simulation depending on the weather data from Meteonorm, which is included in Polysun. Because there is no category for hotels in the SIA norm 380/1, the parameters used for the simulation are a mix between a hospital and a multi-family residential. [10] [11]

	Cooling	Space heating	Hot water
North (Sweden - Örebro)	Very low need, ambient temperature low enough	High need	High need because of many persons
Energy consumption [kWh]	36	214’661	76’572
Suitable storage Method	• UTES or pit storage in combination with a hot water tank. • The cooling needs can be covered by solid media storage realized with concrete walls or even PCM integrated in the concrete.		
Middle (Bern – Switzerland)	Low need, ambient temperature low enough	Medium need	High need because of many persons
Energy consumption [kWh]	2’247	126’136	69’817
Suitable storage Method	• UTES, pit- or ice storage in combination with hot water tank • The cooling needs can be covered by solid media storage realized with concrete walls or even PCM integrated in the concrete.		
	Cooling	Space heating	Hot water
South (Spain – Seville)	High need to keep temperature below 24°C	Very low need, ambient temperature usually high enough	High need because of many persons
Energy consumption [kWh]	138’375	35	53’964
Suitable storage Method	• Ice storage for cooling in combination with hot water tank.		

The following table shows an estimation of the most economical storage technology for a hotel depending on its location.

+ main storage (long term)
o additional storage (short term)

	Hotel – northern climate zone	Hotel – middle climate zone	Hotel – southern climate zone
UTES	++	++	+
ATES	+	+	
Pit storage	++	++	+
Solid media	o	o	o
PCM	o	o	o
Ice storage		+	++
Hot and cold water tank	o/+	o	o

This table can only be used as estimation, the best storage method for an individual building and location has to be evaluated from case to case.

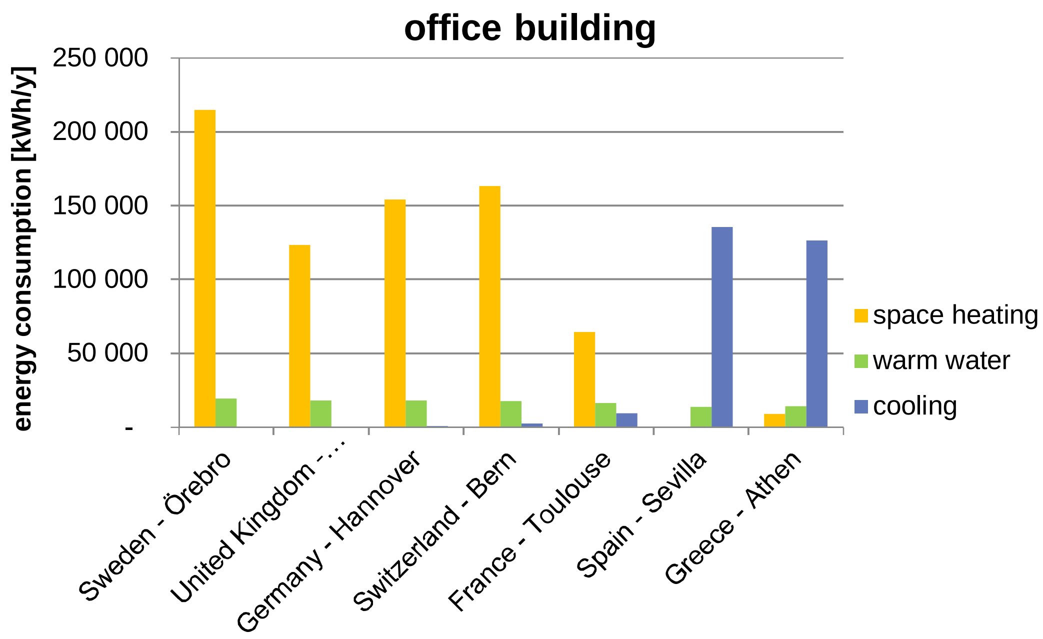
Office building

Building description		
Heated surface	**[m²]**	**2500**
Insulation (U value)	**[W/(m² K)]**	**0.35**
Surface per person [1]	[m²/p]	20
Number of persons	[-]	125
Daily presence[1]	[h]	6
Heating power per person [1]	[W]	80
Internal heat source due to persons	**[W/m²]**	**0.88**
Electricity consumption [1]	[MJ/(y·m²)]	80
Factor heat production from electricity consumption [1]	[-]	0.9
Internal heat source due to installations	**[W/m²]**	**2.28**
Energy consumption for hot water [1]	[MJ/(y·m²)]	25
Hot water daily consumption per person	[l/(p·d)]	8.3
Daily hot water consumption total	**[l/d]**	**1'042**

[1] parameters according to SIA norm 380/1 [10]

Values written bold are calculated from the given values according to the norm and used in Polysun as building parameters

Consumption profile and storage properties



This diagram contains the results of a Polysun simulation depending on the weather data from Meteonorm, which is included in Polysun, and common building parameters of an office building according to the SIA norm 380/1. [10] [11]

	Cooling	Space heating	Hot water
North (Sweden - Örebro)	Low need, ambient temperature low enough, but high internal gains and high solar gains	High need	Low utilization of hot water
Energy consumption [kWh]	63	214’661	19’032
Suitable storage Method	• UTES or pit storage in combination with a hot water tank. • Hot and cold water tank.		
Middle (Bern – Switzerland)	Medium need, waste heat of persons and computers	Medium need	Low utilization of hot water
Energy consumption [kWh]	2’272	162’879	17’350
Suitable storage Method	• UTES or pit storage in combination with a hot water tank. • Ice storage and hot water tank.		
South (Spain – Seville)	High need, waste heat of persons and computers	Very low need	Low utilization of hot water
Energy consumption [kWh]	135’436	158	13’395
Suitable storage Method	• UTES, Pit- or Ice storage for cooling • Hot water tank for DHW.		

The following table shows an estimation of the most economical storage technology for an office building depending on its location.

+ main storage (long term)
o additional storage (short term)

	Office building – northern climate zone	Office building – middle climate zone	Office building – southern climate zone
UTES	+	+	++
ATES	+	+	+
Pit storage	+	+	+
Solid media	o	o	o
PCM	o	o	o
Ice storage	o	++ / o	++ / o
Hot and cold water tank	++	+ / o	o

This table can only be used as estimation, the best storage method for an individual building and location has to be evaluated from case to case.

3.2. Sizing and simulation

Once the system components are chosen, their optimal dimensions have to be evaluated by numeric simulations. Therefore a model of the storage and all connected systems, such as solar panels or others (heat pump, etc.), has to be created in TRNSYS, Polysun or other similar simulation software which allows to quantify all the storage parameters and to optimise its design.

As an example, the solar fraction used for heating or cooling depends on the storage capacity. By using different, previously defined capacity values from an excel file and exporting a simulation result for each value, a diagram showing the relation between solar fraction and storage capacity can be obtained. According to the diagram, the capacity, which results in the highest solar fraction, can be chosen. Special attention to the analysis should be paid, as some results might not be that simple to evaluate because they interfere with others, like typically the investment costs.

3.3. Storage options evaluation for high temperature solar cooling systems

As described before, various sensible and latent heat storage material options are available when designing a solar cooling system. Latent heat materials are known to have higher energy density resulting in lower storage volume. However, it is unclear if there are any energy benefits due to these materials while used in a typical solar cooling application. An approach for evaluating the system level energy benefits while using different storage materials for a solar cooling application is described further.

The solar cooling system with high-temperature, high-efficiency absorption chiller is shown in 9. The typical absorption chiller-based solar cooling plant consists of high temperature solar collectors for generation of heat at high temperatures (> 200 °C). A backup heat source is integrated into the system in parallel to the storage tank to supply heat when solar heat is not available. A triple-effect absorption chiller with cooling tower makes up the cooling generation system. This solar cooling layout is simulated using *TRNSYS*. Details of the component specifications are provided in Table 4. In order to simulate the latent heat storage system, a new numerical model has been developed, validated with experimental data and implemented in the simulation environment as an external library. More details about the numerical model and the validation can be found in [36].

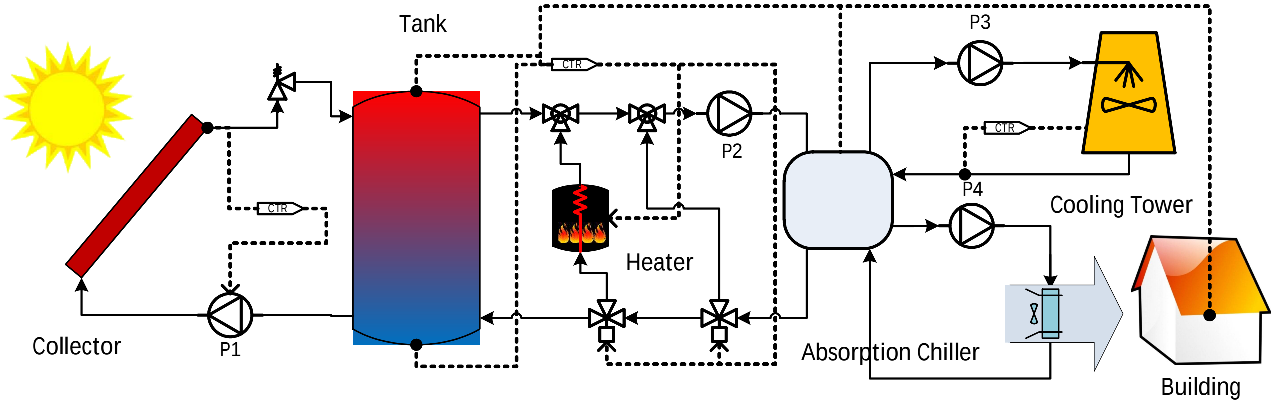


Figure 9. Solar cooling system used for evaluating storage material benefits

Table 4. Solar cooling model details.

Component	Description
Solar collector	Parabolic trough collector. Efficiency parameters for the solar collector are η_0 = 0.689, a_1 = 0.36 W/(m^2 K), a_2 = 0.0011 W/(m^2 K^2) [37].
Back-up system	Instantaneous gas burner with a set point temperature of 220 °C used as the backup. The back-up is positioned to be in parallel with thermal storage tank so that fossil derived heat does not enter the storage tank. The system is provided with heat either via the back-up or the solar thermal storage but not both.
Cooling tower	A wet cooling tower in a counter flow configuration is used. A variable speed fan, driven by a controller, maintained the outlet temperature of cooling water at a constant value of 32 °C.
Pumps	The system used five pumps as shown in Figure **Erreur ! Source du renvoi introuvable.**. The solar pump (P1) worked in variable speed mode with the temperature controller acting to maintain a constant collector outlet temperature by varying pump speed. All other pumps (P2 – P5) operated in ON – OFF mode.

The building load used in this study is representative of a typical office building located in Sydney in Australia. It falls under the category of building type A, according to the Australian Building Code Board (ABCB). The heat load is that of a single storey, of a multiple storey building and it has a fully enclosed square footprint area of ~ 1000 m^2. The dimensions of each of the sides is 31.6 m, and the height (floor to ceiling) is 2.7 m. The walls and fabric are designed to meet minimum requirements provided by the Building Code of Australia (BCA). The internal loads are based on 100 people occupancy and a low infiltration rate (0.25 air changes per hour). Loads associated with lighting and equipment are also included in the model. An indoor temperature of 26 °C has been used as the set point for cooling mode operation. The air conditioning operating time for meeting comfort requirements is set between 7 am to 6 pm, during working days of the week. Over the weekend, no cooling load is specified. Typical summer daily load and monthly cooling requirements are shown in Figure 10.

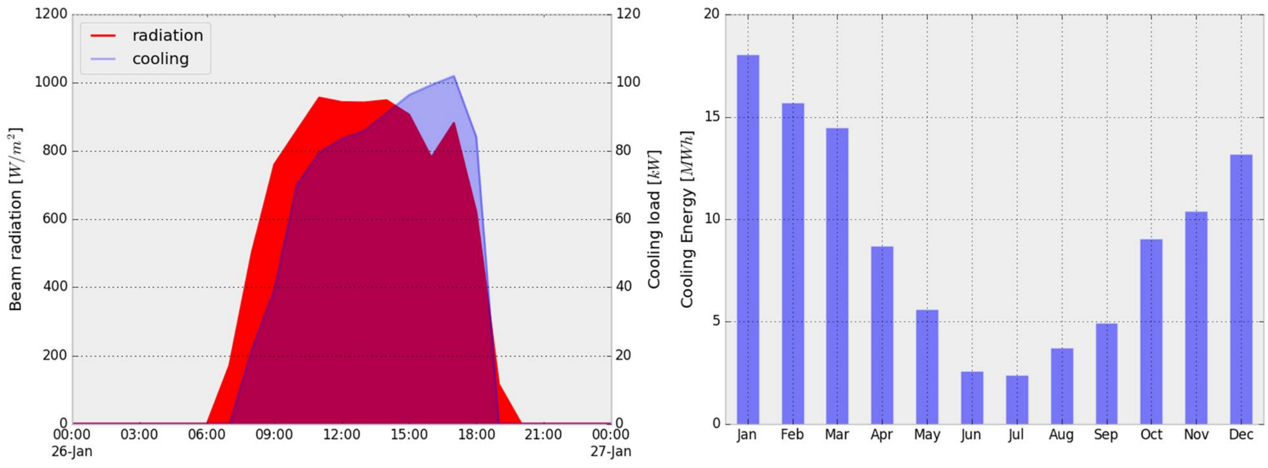


Figure 10. Typical summer daily cooling load (left) and the monthly cooling load (right) for the case study

The chosen building required 108.6 MWh of cooling and 4.0 MWh of heating (the load requirements have been calculated with *TRNSYS* assuming room set-point temperatures of 20 °C and 26 °C for heating and cooling). Since the building requires predominately cooling, the heating load was not considered in the simulations. The maximum cooling demand over an hour is 85 kW. The load has been scaled to match a triple-effect chiller nominal capacity of 103 kW. A typical commercial cooling tower specification has been used to match the chiller nominal characteristics. The simulation control method adopted is the energy rate control: every time-step the system has to supply the right amount of energy required to keep the temperature of the building below the 26 °C set-point. The details of the control scheme used in the simulations are described in [36].

3.3.1. Thermal storage material selection and system design

Two sensible and two latent heat storage materials have been chosen for the studies. Water and thermal oil have been chosen as the sensible heat storage media. The nominal operating temperature of the triple effect chiller is 210 °C. Hence, phase change materials with phase change temperature range of 220 °C to 230 °C have been chosen for the studies. $KNO_3/NaNO_3$ eutectic salt (known as solar salt) has a phase change temperature of around 220 °C. Moreover, these salts are commercially available. However, these salts have poor thermal conductivity that can limit the charging and discharging effectiveness of the storage system. Hence, a high conductivity metal phase change material with phase change temperature of 230 °C [37] has been chosen as the second phase change material for evaluation.

Table 5 provides a summary of material properties used in the simulations.

Table 5. Thermal storage materials properties used in the simulations

Storage material	HTF used	Mass Density (kg/m^3)	Specific Heat Capacity (kJ/(kg K))	Thermal conductivity (W/(m K))	Phase Change Temperature (°C)	Latent Heat (kJ/kg)	Energy Density* (kWh/m^3)	Specific Energy* (kWh/kg)	Cost (USD/ kWh)
Water @ 20bar, 200°C	Water	853	4.49	0.664	-	-	21.3	2.5e-2	0.02
Therminol 55 @ 204°C	Therminol	737	2.56	0.107	-	-	10.5	1.4e-2	117.4
Solar salt ($KNO_3/NaNO_3$)	Therminol	2000	1.5	0.5	221	100.7	55.9	2.8e-2	n.a.
Aluminium-Tin Alloy (AlSn)[1]	Therminol	6823(s)/ 6500(l)	0.237(s)/ 0.263(l)	75(s)/ 42(l)	231/232	50	92.5	1.4e-2	n.a.

Generic approaches for comparing sensible and latent heat storage systems have not been clearly established. This issue is compounded by the wide variety of approaches used for designing a PCM based storage system. Castell and Solé [47] have summarized design methodologies used in liquid – solid phase change storage systems. Amin et al., [48] have suggested that both volume of PCM in the storage system, and energy storage effectiveness are parameters to consider when designing a PCM based storage system. In this design, the following constraints have been applied to enable direct comparison of different storage materials:

a. Nominal total energy stored in the storage materials is made constant for all the scenarios. Sensible energy storage systems directly store the heat in the fluid resulting in an increase in the temperature. In order to compute the energy density, a temperature difference of 20 °C is chosen for sensible heat storage materials. A shell and tube design with PCM in-tube configuration has been chosen for latent heat storage system studies. As a result, this system also stores energy in the tubes and in the heat transfer fluid. The stored latent energy in the PCM was chosen to be 80 % of the total energy stored. The rest of the stored energy is equally distributed between the tube material and the HTF. Increase in storage time is then achieved by either adding more tubes or increasing the tube length.
b. When comparing latent heat materials, the heat transfer area of the heat exchanger has been kept constant so that a given PCM based storage system does not perform better due to superior heat transfer design. While identifying design parameters for the shell and tube heat exchanger, it has been ensured that the storage system heat transfer effectiveness is above 0.8. This effectiveness has been estimated a priori using nominal discharging condition (storage fully charged at maximum temperature).
c. Minimum heat loss area on the shell side. The area of heat losses has been constrained in order to limit the search space of the design configurations, while insuring optimal performance of the storage. For a cylinder, this constraint leads to a shell diameter to height ratio of ~1.

Energy storage values have been chosen such that the storage system can provide 0.5 hours to 5 hours of storage, to allow heat supply in cases that range from cloud coverage through overcast afternoon.

The latent heat storage design steps are as follows:

1. Estimate total energy stored by the storage system from design requirements (nominal chiller capacity, COP):

$$E_{st} = \frac{Q_{nom}}{COP} \times storage\ time \tag{1}$$

2. Obtain the total volume of the system and the volume of HTF, PCM and the tube from the volumetric energy storage density data and application of constraint (a). This results in:

$$V_{shell} = V_{HTF} + V_{tube} + V_{PCM} \tag{2}$$

$$V_{shell} = \frac{0.1E_{st}}{E_{v,htf}} + \frac{0.8E_{st}}{E_{v,pcm}} + \frac{0.1E_{st}}{E_{v,t}} \tag{3}$$

3. The design of the shell and tube heat exchanger requires additional dimensional details of tubes (outer and inner diameter and length), shell size and the number of tubes. From constraint (c), the diameter of the shell is equal to its height. Thus one obtains the diameter and height of the shell as:

$$D_{shell} = H_{shell} = \sqrt[3]{\frac{4V_{shell}}{\pi}} \tag{4}$$

Considering the tube length (L) is equal to shell height, length of the tubes can be estimated.

4. From design constraint (a), we obtain:

$$\frac{V_{pcm}}{V_{tube}} = \frac{N\pi D_i^2 L/4}{N\pi(D_o^2 - D_i^2)L/4} = \frac{D_i^2}{(D_o^2 - D_i^2)} \tag{5}$$

The tube dimensions can then be chosen from commercially available sizes (DN 15 – 20 – 25 – 32 – 40 – 50) to fit equation.

5. Finally, the number of tubes can be obtained from the total volume of the storage material once the tube inner diameter and the length are known.

Design steps 1 – 5 were followed while deciding the dimensions of the second latent heat storage material. Two levels of sanity checks were carried out to ensure the design meets the requirements. The first one is the constraints fulfilment, established by the equations below:

i. Conditions set by constraint (b) results in:

$$\frac{D_{o,salt}}{D_{o,AlSn}} = \frac{N_{AlSn}}{N_{salt}} \frac{L_{AlSn}}{L_{salt}} \tag{6}$$

ii. Conditions set by constraint (a) results in:

$$\frac{E_{v,salt}}{E_{v,AlSn}} = \left(\frac{D_{i,Alsn}^2}{D_{i,salt}^2}\right) \tag{7}$$

As a second sanity check, the shell diameter was always compared with the minimum diameter required for arranging the chosen tubes inside the shell diameter, calculated from the *"circles in circle"* optimization problem [49] to check if the design is realistic. For example, in the case of salt with 0.5 hours of storage, the estimated shell diameter is 1.02 m and the total number of tube chosen is 302. The minimum physical diameter for best packing of 302 tubes with a tube outer diameter of 48.3 mm is 0.913 m.

Since the design process requires approximations (e.g. rounding off the tube length to nearest integer and the choosing a combination of inner and outer tube diameters to the nearest e available commercial sizes), the chosen configurations matched the total energy stored and heat transfer area design constraints within 3 % relative error.

3.3.2. Solar fraction benefits

Annual simulations have been carried out to compare different storage materials on overall system performance. A parametric analysis of the collector area and storage tank dimensions have been carried out to investigate the variability of system performance and its optimal design. Four levels of collector area (1 to 4 m^2/kW_c) and storage duration (30 min, 1, 3 and 5 hours) have been used to evaluate the effect of component sizing on the system benefits. The results have been presented for two cooling scenarios, namely the system operating with a constant cooling load and a variable cooling load. In the first, the chiller is working at constant nominal operational conditions in order to simulate the system with base load operation, while in the second scenario the chiller is allowed to operate in part load, with a capacity modulation of 40 % to 120 % of the nominal.

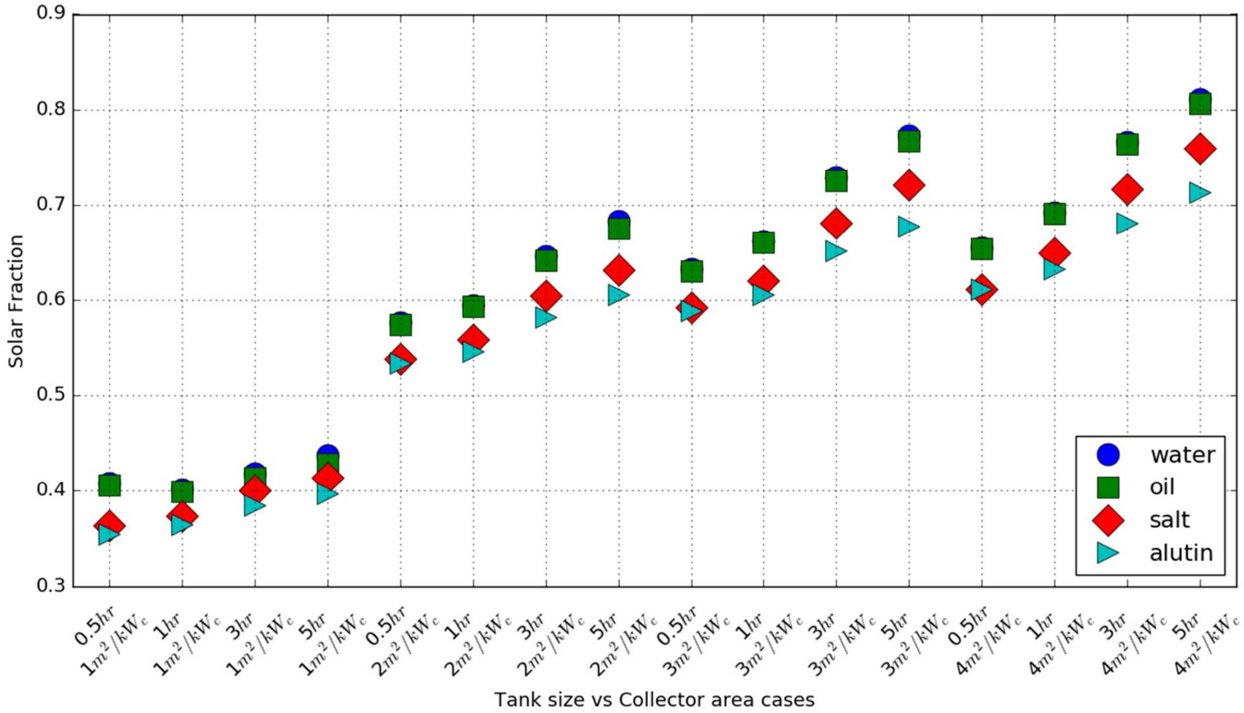


Figure 11. Solar fraction for sensible and latent heat energy storage systems with constant cooling load

Figure 11 shows the variation of solar fraction with storage time and collector area for different storage materials at constant cooling load. As expected, solar fraction increases with increasing collector area for all the storage materials cases. For a given collector area, the solar fraction increases with increasing storage volume. Sensible and latent storage materials have similar solar fraction values at low collector areas whereas for higher collector area values, the sensible materials have a higher solar fraction than the latent heat materials. It is seen that the sensible thermal storage materials have high solar fraction despite having higher tank losses due to their larger size (Figure 12). The lower solar yield for latent heat storage scenarios is attributed to the higher collector set point temperature required to achieve the phase change of these materials. Solar salt has a phase change temperature of 220 °C, AlSn has a phase change temperature of 230 °C. As a result, the collector outlet temperature set points are 20 °C or 30 °C higher than the set points used by sensible heat materials (210 °C). Additionally, for sensible heat storage materials, the heat transfer fluid is also the storage media whereas latent heat materials require an additional heat exchanger resulting in higher HTF fluid temperature requirements. Due to higher temperature in the tank and the high collector outlet temperature requirements, solar collectors operate with higher efficiency, delivering improved solar fraction over latent heat materials.

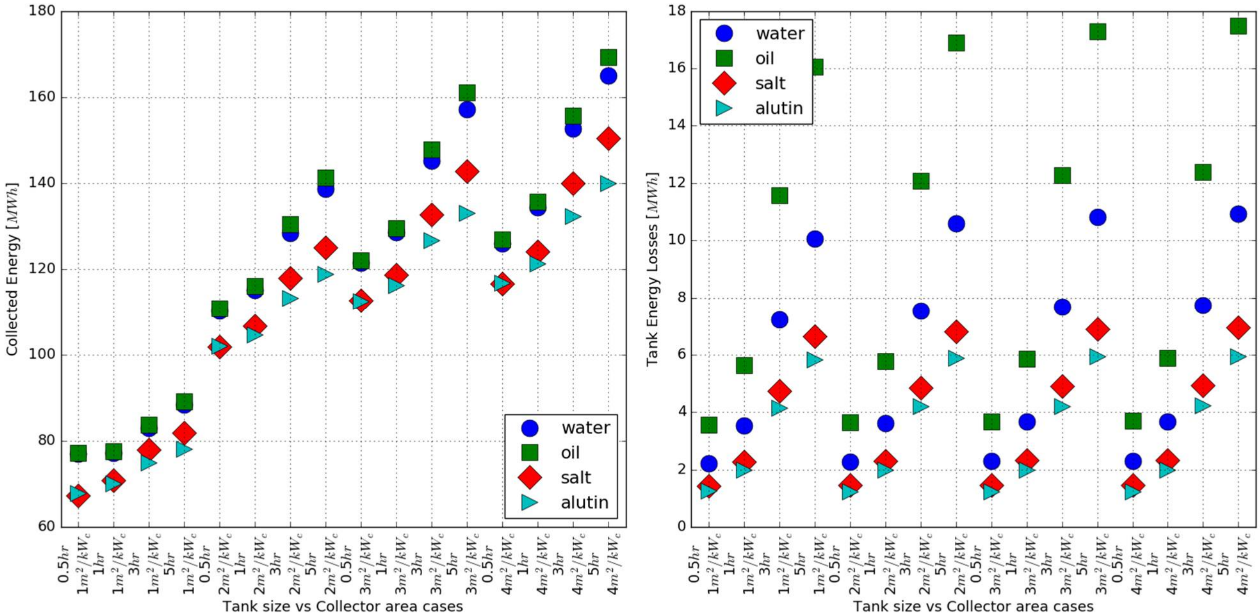


Figure 12. Solar heat collected, tank losses for the system with constant cooling load

The solar fraction of the system is generally greater for the variable cooling load case compared with the constant full load case (Figure 13). This is because of the lower temperature requirement of the chiller at part loads. Similar to a constant load scenario, higher specific collector area and thermal storage volumes increase the solar fraction. However, the difference between sensible and latent heat materials performance is more accentuated due to the high phase change temperature of the PCMs. A comparison of solar fraction benefits for constant cooling load and variable cooling load shows latent heat materials perform poorly compared to sensible heat storage materials when delivering heat to a variable cooling load. This is attributed to the capability of sensible heat materials to deliver heat at lower temperatures, while latent heat materials are less flexible due to the fixed phase change temperature.

This suggests that it may be appropriate to choose a phase change material with a temperature that is better aligned with load weighted mean operating temperature of the chiller. Options to improve the solar fraction for a variable cooling load system such as varying the control strategy and matching the storage material phase change temperature to chiller operational requirements will be taken up in a future investigation.

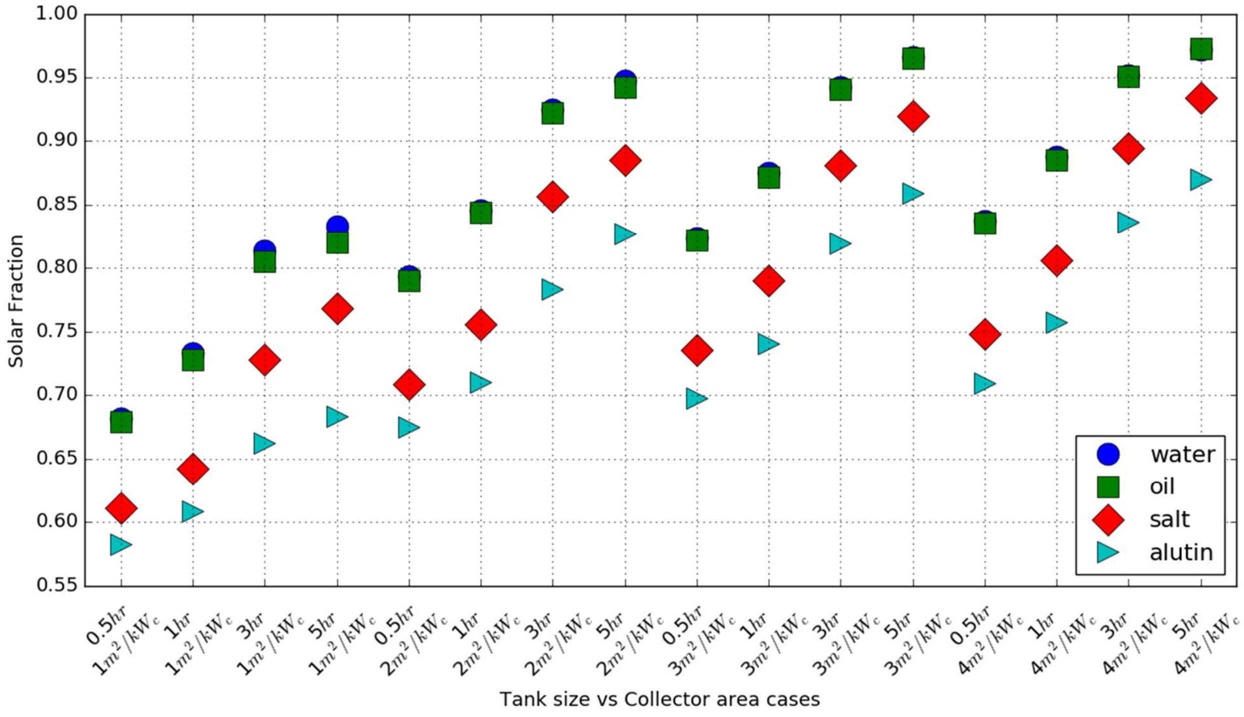


Figure 13. Solar fraction for sensible and latent heat energy storage systems with variable cooling load

4. Electrical Energy Storage (EES)

The following paragraphs describe the relevant electrical storage methods for domestic applications using solar driven heat pump devices [12].

The conventional large-scale electricity producers have little or no storage facility. The electricity transmission and distribution systems are operated for the simple one-way transportation from remote and large power plants to consumers. This means that electricity must always be used precisely when produced. However, the demand for electricity varies considerably emergently, daily and seasonally. This leads to inefficient, overdesigned and expensive plants. EES allows energy production to be de-coupled from its supply, self-generated or purchased.

4.4. Objectives of the Electrical Energy Storage (EES)

Electrical Energy Storage (EES) refers to a process of converting electrical energy from a power network into a form that can be stored for converting back to electrical energy when needed. It can provide substantial benefits including load following, peaking power and standby reserve and it can increase the net efficiency of thermal power sources while reducing harmful emissions [[13]; [14]; [15]]. Moreover, EES systems are critically important to intermittent renewable energy supply systems such as solar photovoltaic, wind turbine and wave.

EESs have numerous applications covering a wide spectrum, ranging from large-scale generation and transmission-related systems, to distribution network and even customer/end-user sites. The EES technologies provide three primary functions of energy management, bridging power and power quality, and reliability.

In terms of the function, EES technologies can be categorised into those that are suitable for power quality; and those designed for energy management. Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage system (CAES), Thermal Energy Storage system (TES), large-scale batteries, flow batteries, fuel cells and solar fuel fall into the category of energy management, whereas capacitors/supercapacitors, SMES, flywheels and batteries are in the category of power quality and reliability.

4.5. Classification and technical maturity

The EESs are classified as follow:

1) Electrical energy storage: (i) Electrostatic energy storage including capacitors and supercapacitors; (ii) Magnetic/current energy storage including Superconducting Magnetic Energy Storage system (SMES).

2) Mechanical energy storage: (i) Kinetic energy storage (flywheels); (ii) Potential energy storage (PHS and CAES).

3) Chemical energy storage: (i) Electrochemical energy storage (conventional batteries such as lead-acid, nickel metal hydride, lithium ion and flow-cell batteries such as zinc bromine and vanadium redox); (ii) chemical energy storage (fuel cells, molten-carbonate fuel cells – MCFCs and Metal-Air batteries); (iii) thermochemical energy storage (solar hydrogen, solar metal, solar ammonia dissociation–recombination and solar methane dissociation–recombination).

4) Thermal energy storage: already discussed.

The technical maturity of the EES systems is shown in Figure 14 [12].

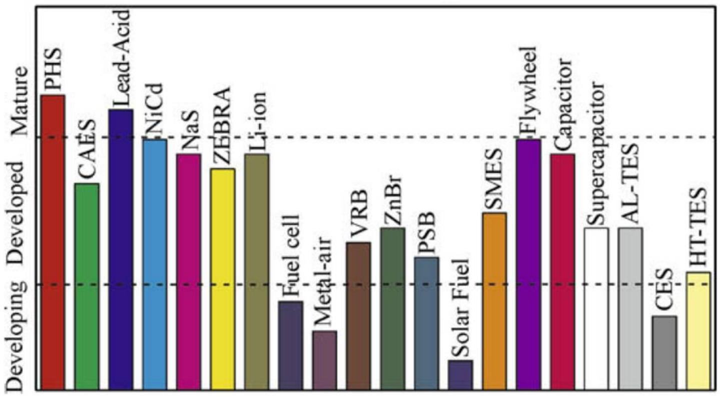


Figure 14. Technical maturity of EES systems [12]

In this report, the focus is on the EES systems in a very well developed state as well as in the maturity state, and on those categorised suitable for energy management and for application customer/end-user sites.

4.6. The conventional battery

Rechargeable/secondary battery is the oldest form of electricity storage, which stores electricity in the form of chemical energy. A battery is comprised of one or more electrochemical cells and each cell consists of a liquid, paste, or solid electrolyte together with a positive electrode (anode) and a negative electrode (cathode). During discharge, electrochemical reactions occur at the two electrodes generating a flow of electrons through an external circuit. The reactions are reversible, allowing the battery to be recharged by applying an external voltage across the electrodes. They can respond very rapidly to load changes and accept co-generated and/or third-party power, thus enhancing the system stability. Unfortunately, most batteries contain toxic materials [15]. Hence, the ecological impact from uncontrolled disposal of batteries must always be considered. Batteries that are either in use and/or potentially suitable for utility scale battery energy and storage applications include lead acid, nickel cadmium, sodium nickel chloride and lithium ion.

4.6.3. Lead acid batteries

Lead acid batteries (PbA) are the oldest and most widely used rechargeable electrochemical devices. A lead acid battery consists of (in the charged state) electrodes of lead metal and lead oxide in an electrolyte of about 37% sulphuric acid. In the discharged state both electrodes turn into lead sulphate and the electrolyte loses its dissolved sulphuric acid and becomes primarily water.

There are several types of lead acid batteries including the flooded battery requiring regular topping up with distilled water, the sealed maintenance free battery having a gelled/absorbed electrolyte, and the valve-regulated battery.

Lead acid battery has a low cost ($300–600/kWh), a high reliability and efficiency (70–90%). It is a popular storage choice for power quality; its application for energy management, however, it has been very limited due to its short cycle life (500–1000 cycles) and low energy density (30–50 Wh/kg) due to the inherent high density of lead. Lead acid batteries also have a poor low temperature performance and therefore they require a thermal management system.

4.6.4. Nickel cadmium batteries

Nickel cadmium batteries (NiCd) contain a nickel hydroxide positive electrode plate, a cadmium hydroxide negative electrode plate, a separator, and an alkaline electrolyte. NiCd batteries usually have a metal case with a sealing plate equipped with a self-sealing safety valve. The positive and negative electrode plates, isolated from each other by the separator, are rolled in a spiral shape inside the case.

NiCd batteries have a reasonable energy density (50–75 Wh/kg), a robust reliability and very low maintenance requirements, but relatively low life cycle (2000–2500).

The main drawback of NiCd batteries is the relatively high cost (~$1000/kWh) due to the expensive manufacturing process. Cadmium is a toxic heavy metal hence posing issues associated with the disposal of NiCd batteries. NiCd batteries also suffer from ‘‘memory effect”, where the batteries will only take full charge after a series of full discharges. Proper battery management procedures can help to mitigate this effect.

4.6.5. Sodium nickel chloride or ZEBRA

The sodium nickel chloride battery [16] is better known as the ZEBRA battery. It is a high temperature (~300°C) system that uses nickel chloride as its positive electrode and has the ability to operate across a broad temperature range (-40 ~ +70°C) without cooling.

With an energy density of about 120Wh/kg and power density of about ~150 W/kg, they represents a considerable improvement over the PbA and NiCd battery technology.

The company, MES - DEA S.A. (Swiss), now sell complete ZEBRA Battery systems.

4.6.6. Lithium ion batteries

The cathode in this kind of battery is a lithiated metal oxide ($LiCoO_2$, $LiMO_2$, $LiNiO_2$ etc.) and the anode is made of graphitic carbon with a layering structure or more recently is made of titanate (LTO). The electrolyte is made up of lithium salts (such as $LiPF_6$) dissolved in organic carbonates. When the lithium ion (Li-ion) battery is charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between the carbon layers as lithium atoms. This process is reversed during the discharge process.

Improved material developments have led to vast improvements in terms of the energy density (increased from 75 to 200 Wh/kg) and cycle life (increased to as high as 25’000 cycles for the LTO chemistry). The efficiency of Li-ion batteries is higher than 95% – another important advantage over other batteries.

The main drawback of Li-ion batteries is the fact that the charging current is limited to 1.5- 2 C-rate. The cost has seen a considerable reduction from 210 up to 900 $600/kWh.

In the following paragraphs, we first focus on two kinds of batteries: vanadium redox (VRB), and zinc bromine (ZnBr); they belong to the flow battery category. Then we described a promising Li-ions chemistry, the **Lithium Titanium Oxide Cell (LTO)**.

4.7. The flow battery

A flow battery is a form of a battery in which the electrolyte contains one or more dissolved electroactive species flowing through a power cell in which the chemical energy is converted to electricity. The reaction is reversible allowing the battery to be recharged. In contrast to conventional batteries, flow batteries store energy in the electrolyte solutions. They can release energy continuously at a high rate of discharge for up to 10 h.

4.7.7. Vanadium redox battery

Vanadium redox battery (VRB) stores energy by employing vanadium redox couples. These are stored in mild sulphuric acid solutions (electrolytes). During the charge/discharge cycles, H^+ ions are exchanged between the two electrolyte tanks through the hydrogen-ion permeable polymer membrane. The efficiency can be as high as 85%. The energy density is relatively low (10–30 Wh/kg).

4.7.8. Zinc bromine battery

In each cell of a Zinc bromine battery (ZnBr), two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane. During discharge, Zn and Br combine into zinc bromide. This will increase the Zn^{2+} and Br-ion density in both electrolyte tanks. During charge, metallic zinc will be deposited (plated) as a thin film on one side of the carbon-plastic composite electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents (organic amines) to make thick bromine oil that sinks down to the bottom of the electrolytic tank. It is allowed to mix with the rest of the electrolyte during discharge. The net efficiency of this battery is about 75%.

4.8. Technical characteristics

In Table 6, and Table 7, the comparison of technical characteristics of the described previously EES systems is reported.

Table 6. Comparison of technical characteristics of the described EES systems [12]

Systems	Power rating and discharge time		Storage duration		Capital cost		
	Power rating	Discharge time	Self discharge per day	Suitable storage duration	$/kW	$/kWh	¢/kWh-Per cycle
Lead-acid	0–20 MW	Seconds–hours	0.1–0.3%	Minutes–days	300–600	200–400	20–100
NiCd	0–40 MW	Seconds–hours	0.2–0.6%	Minutes–days	500–1500	800–1500	20–100
ZEBRA	0–300 kW	Seconds–hours	~15%	Seconds–hours	150–300	100–200	5–10
Li-ion	0–100 kW	Minutes–hours	0.1–0.3%	Minutes–days	1200–4000	600–2500	15–100
VRB	30 kW–3 MW	Seconds–10 h	Small	Hours–months	600–1500	150–1000	5–80
ZnBr	50 kW–2 MW	Seconds–10 h	Small	Hours–months	700–2500	150–1000	5–80

Table 7. Continuation of the comparison of technical characteristics of the described EES systems [12]

Systems	Energy and power density				Life time and cycle life		Influence on environment	
	Wh/kg	W/kg	Wh/L	W/L	Life time (years)	Cycle life (cycles)	Influence	Description
Lead-acid	30–50	75–300	50–80	10–400	5–15	500–1000	Negative	Toxic remains
NiCd	50–75	150–300	60–150		10–20	2000–2500		
ZEBRA	100–120	150–200	150–180	220–300	10–14	2500+		
Li-ion	75–200	150–315	200–500		5–15	1000–10,000+		
VRB	10–30		16–33		5–10	12,000+	Negative	Toxic remains
ZnBr	30–50		30–60		5–10	2000+		

All the costs per unit energy shown in Table 7 have been divided by the storage efficiency to obtain the cost per output (useful) energy. The per cycle cost is defined as the cost per unit energy divided by the cycle life which is one of the best ways to evaluate the cost of energy storage in a frequent charge/discharge application. For example, while the capital cost of lead acid batteries is relatively low, they may not necessarily be the least expensive option for energy management due to their relatively short life for this type of application. The costs of operation and maintenance, disposal, replacement and other ownership expenses are not considered.

The capital cost of energy storage systems can be significantly different from the estimations given here due to, for example, breakthroughs in technologies, time of construction, location of plants, and size of the system.

The cycle efficiency of EES systems during one charge-discharge cycle is illustrated in Figure 15. The cycle efficiency is the ‘‘round-trip” efficiency defined as E_{out}/E_{in}, with E_{out} and E_{in} being the cycle efficiency, electricity input and electricity output, respectively. The self-discharge loss during the storage is not considered.

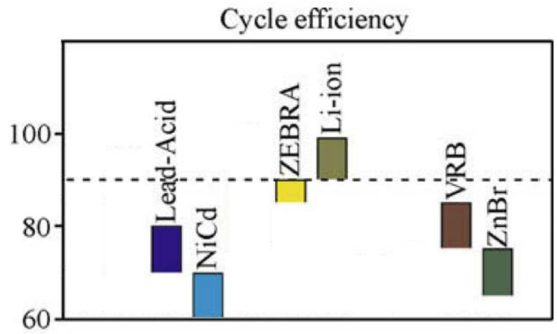


Figure 15. Cycle efficiency of EES systems [12]

There are differences in energy density of the same type of EES made by different manufacturers. In a Swiss study [17] is reported the Figure 16, which highlights the uncertainty in literature for the energy capacity costs, round trip efficiency, calendrical life and cycle life across technologies.

There is a trade-off between the capital cost and round-trip efficiency, at least to some extent. For example, a storage technology with a low capital cost but a low round-trip efficiency may well be competitive with a high cost and high round-trip efficiency technology.

The power density (W/kg or W/litre) is the rated output power divided by the volume of the storage device. The energy density is calculated as a stored energy divided by the volume. The volume of the storage device is the volume of the whole energy storage system including the energy-storing element, accessories and supporting structures, and the inverter system [12].

In their study, Battke *et al.* stated: "although lead–acid and lithium-ion each exhibit cost leadership by mean life cycle costs for specific applications, the respective relative advantage is not significant." Therefore, a competition still exists among the analysed battery technologies and so far, a leading technology has yet to emerge in any of the investigated applications. However, lead-acid batteries and NiCd batteries are expected to be gradually implemented for energy management with decreasing price and increasing cycle life.

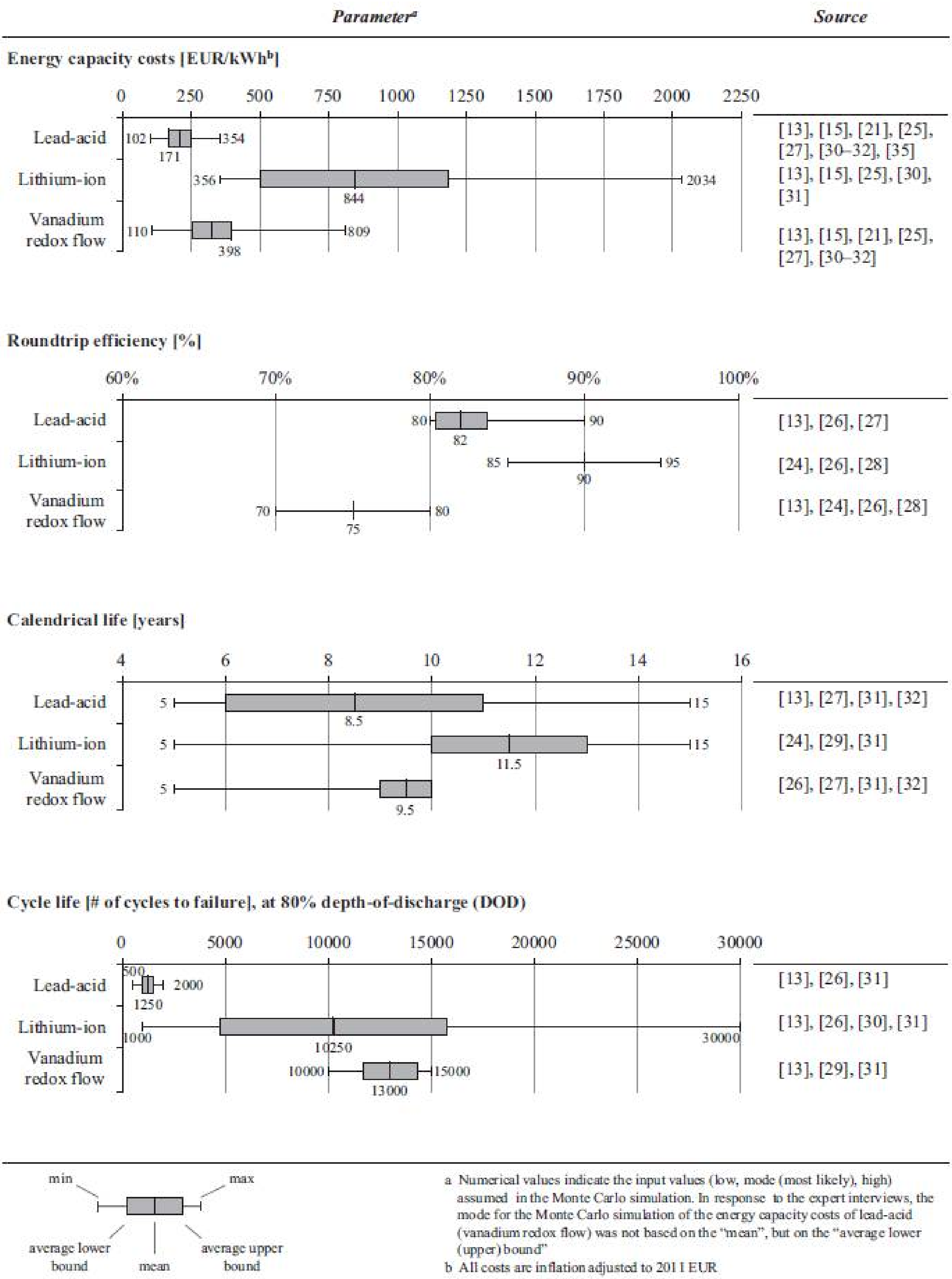


Figure 16. The uncertainty of energy capacity costs, roundtrip efficiency, calendrical life and life cycle at 80% depth-of-discharge reported in literature [17]

4.9. The Lithium Titanium Oxide Cells (LTO)

The main structural drawback of the Li-ion cell is the graphite composing the anode of the cell. Even if this material increases the energy density of the cell, its decomposition and micro cracking during the discharge process limits the cycle life of the cell. It is worth noting that a discharge current twice higher than 1C-rate decreases the cycle lifetime of a factor 3. A discharge current higher 4 times higher than 1C-rate reduce dramatically the cycle lifetime (few hundreds of cycles).

Last years, a new Li-ion chemistry has been introduced in the market, the Lithium Titanium Oxide cell (LTO) and its two main manufacturers in the world are GWL Power and Leclanché SA.

The main characteristic of this chemistry is that the graphite normally composing the anode is replaced by titanate; this involve the following main advantages:

i) The cycle-life pass from 5000-8000 cycles with a depth of discharge equal to 80% (for classic graphite Li-ion cells) up to 20.0000-25.000 cycles with a depth of discharge equal to 100%;

ii) The cell can be discharged with a current even 6 times higher than 1C-rate without any dramatic ageing process. With a 4C-rate the cycle life is equal to 15.000 cycles;

iii) The cell can be charged with a current even 4 times higher than 1C-rate without any dramatic ageing process. With a 4C-rate the cycle life is equal to 15’000 cycles while a classic graphite Li-ion cells can be destroyed after 100 cycles.

iv) The self-discharge process is limited to 3-4% every 6 months compared to 4-5% per month with classic graphite Li-ion cells.

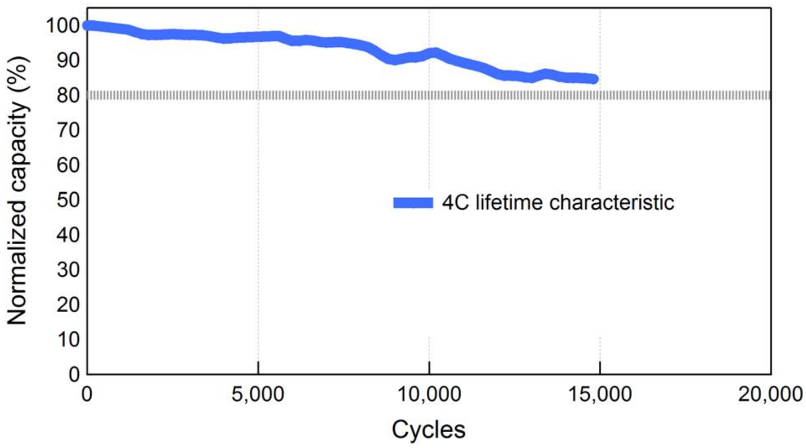


Figure 8. Life cycle of a LTO cell with symmetric charge and discharge 4C-rate (Leclanché SA)

However, the energy density of a LTO cells is of 70-80 Wh/kg while the one for classic graphite Li-ion cells is of 120-200 Wh/kg.

4.10. Case study for EES

The following paragraph reports the energy requirements for the production in a stand-alone PV-battery system in a specific reference case [[18]; [19]]. The batteries in Table 8 were compared in a PV-battery system.

Table 8. Description of the batteries used in the PV-battery system [[18]; [20]; [21]; [22]; [23]; [24]]

Technology	Abbreviation	Model	Description	Positive electrode or catholyte	Electrolyte	Negative electrode or anolyte
Li-ion	Li-ion	SAFT Li-ion VL 50 E Mixed oxide: LiNi0.8(Co+M) 0.2 O_2[a]	Cylindrical, sealed maintenance free cells	$Li_{1-x}MeO_2$/ $LiMeO_2$[a]	PC, $LiPF_6$	Li_xC/C
Nickel–cadmium	NiCd	SAFT Sunica.plus 1110	Pocket plate, thick electrodes, felt-isolated, vented, flooded electrolyte	$NiOOH/Ni(OH)_2$	20% KOH (1.2 kg/dm^3)	$Cd/Cd(OH)_2$
Lead–acid	PbA	Tudor Exide 16OGi 1260	Vented, pasted flat plates, flooded electrolyte[c]	$PbO_2/PbSO_4$	1.3 kg/dm^3 H_2SO_4	$Pb/PbSO_4$
Vanadium	VRB	Sumitomo Electric Industries	Redox flow, 4 stacks × 80 cells (serial)	$VO_2^+(aq)/VO^{2+}(aq)$	1.8 M V in 4.2 M H_2SO_4	$V^{2+}(aq)$/ $V^{3+}(aq)$
Zinc–bromine	ZnBr	ZBB research	Redox flow	$Br_2(aq)/2\ Br^-(aq)$	2.25 M $ZnBr_2$	$Zn/Zn^{2+}(aq)$

[a] Me = mixed oxide lithiated cathode $LiNi_{0.8}(Co{+}M)0.2\ O_2$. M = different combinations of Mn, Al and other metals are used.

[c] Advanced gelled electrolyte PbA is assumed for high performance values [20].

The PV modules are assumed to be based on multi-crystalline silicon (mc-Si). Table 9 shows that the energy efficiencies were estimated to be 0.12–0.13 for the PV modules, 0.90–0.95 for the charge regulator and 0.92–0.94 for the inverter. Corrections for power or temperature deviation, incomplete utilisation of irradiation etc. are not explicitly considered for these components, but they are assumed to be included in these efficiency ranges.

For batteries requiring pumps and auxiliary components, these losses are included.

The annual solar irradiation (H) was assumed to be 1.7 MWh/m^2 yr., representing medium irradiation levels, which can be found in Southern Europe [25]. The maximum solar irradiance (Sp) is assumed to be 1000 W/m^2.

Table 9. Energy efficiencies □I of the PV-battery system components [18]

Components	η_i
1 PV (mc-Si)	0.12–0.13
2 Charge regulator	0.90–0.95
3 Batteries	
Li-ion	0.85–0.95
PbA	0.70–0.84
NiCd	0.65–0.85
VRB	0.60–0.80
ZnBr	0.60–0.73
4 Inverter	0.92–0.94
5 Air conditioning	

The end of battery service life is when the battery capacity has reached 80% of its initial capacity, when the internal equivalent resistance reached 200% of its initial value or when it fails to function. The effects of ambient temperature on the performance and service life of redox flow batteries are limited since their operating temperatures are regulated by pumping of the electrolytes or by thermal management systems.

When Li-ion, NiCd and PbA batteries are used in applications with shallow cycling, their service life normally will be limited by float life.

In systems where the cycling is deep, but occurs only a few times a year, temperature dependent corrosion processes is the normal life-limiting factor, even for batteries with low cycle life [26]. In systems with deep daily cycling, the cycle life determines the service life of the battery [[27]; [21]].

The battery service life in Table 10 is defined as t_{3limit}, which is the service life limited by either the cycle life or the float service life, depending on which life limiting condition will be reached first.

PbA batteries every 10°C increase in temperature reduces service life by 50%. Valve regulated lead-acid batteries have been shown to have >15 years float service life at 20°C and >10 years at 25°C [26]. The rate of ageing for NiCd batteries is about 20% reduction in life for 10°C increase in temperature [29].

The parameter settings for the evaluation of the PV-battery system are reported in Table 6.

Air conditioning unit is not used to cool the battery when the ambient temperature is high (Air condition in operation off).

Primary fossil energy requirements (GJ/yr.) for production and transportation of PV-battery systems are reported in Table 12 and Figure 18 (annual electricity output from PV-battery system (MJ/yr.) = 197 GJ/yr. and the uncertainty is ±14 – 61%).

Table 10. Service life of PV-battery system components [18]

Component	t_i (yrs)	$t_{3,\text{limit}}$[f] (yrs)
1 PV array (mc-Si)	30	
2 Charge regulator	10	
3 Batteries		
VRB[g]		15–20[h]
Li-ion		14–16[h]
NiCd		13–16
ZnBr		8.0–10[h]
PbA[k]		2.5–5.5
4 Inverter	10	
5 Air conditioning	8	

[f] Limited by either the cycle life or the float service life, depending on which life-limiting condition will be achieved first.

[h] Limited by float service life when cycled one cycle per day.

[g] Ionic membranes have to be replaced every 10 years.

[k] The higher values represent the performance of advanced gelled electrolyte PbA [20].

Table 11. Parameter settings for evaluation of the PV-battery system [18]

Service life ($t_{3,\text{limit}}$[a])	Battery temperature (25 or 40 °C)	Air conditioning in operation (on or off)	Recycling battery materials (100% or 0)	Transportation 3000 km (truck or plane)
$t_{3,\text{limit}}$	25	Off	100	Truck

[a] Limited by either the cycle life or the float service life, depending on which life-limiting condition will be achieved first.

Table 12. Energy requirements (GJ/yr.) for production and transportation of PV-battery systems [18]

Li-ion	133
NiCd	209
PbA	275
VRB	145
ZnBr	135

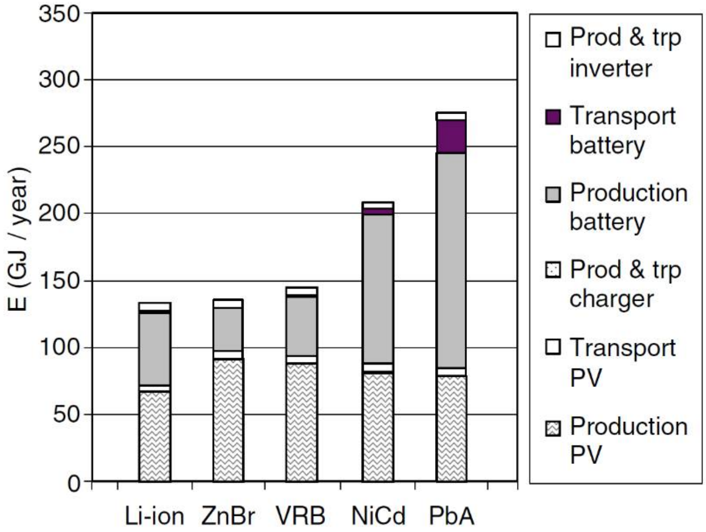


Figure 18. Energy requirements for production and transport of various PV-battery systems for the reference case. The uncertainty is ±14 – 52% [18]

4.10.9. Energy return factor

The energy return factor is used as an indicator of how efficiently a device (such as a PV-battery system) uses non-renewable energy in comparison to an alternative method of producing the same service. In this case, the alternative means of producing electricity locally would be a Diesel generator. It is convenient to use primary fossil energy when the energy return factor is calculated.

Both systems have the same output E_{use} (MJ/yr.).

The energy return factor, *f*, is then the ratio between the replaced fossil energy (diesel) and the fossil energy required producing the PV-battery system:

$$f = \frac{E_{G0}}{E_{i,\mathrm{pf}}} \tag{8}$$

where E_{G0} (MJ/yr.) is the average annual gross primary fossil energy use of the Diesel system and $E_{I,pf}$ (MJ/yr.) is the average annual primary fossil energy required for production and transport.

Energy return factors of the PV-battery systems for the reference case are reported in Figure 19.

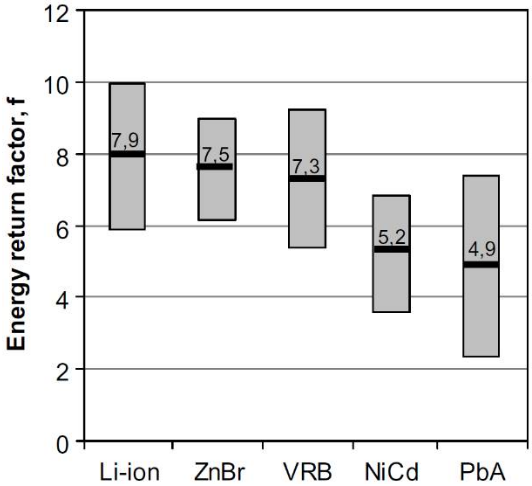


Figure 19. Energy return factors for the PV-battery systems for the reference case. The variation in the average value is ±14% to 52% [19]

4.10.10. Overall efficiency of the battery system

The overall efficiency of the battery system (charger, battery and inverter), η_B^*, is the ratio between the output from the battery system, E_{use} (MJ/yr.), and the total inputs, translated into an electricity equivalent, E_G (MJ/yr.):

$$\eta_B^+ = \frac{E_{use}}{E_G} \quad (9)$$

Overall battery efficiencies, including production and transport of charger, battery and inverter for the reference case are reported in Figure 20.

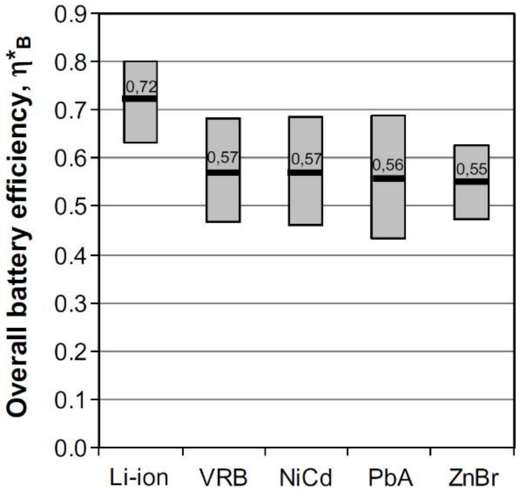


Figure 20. Overall battery efficiencies including production and transport of charger, battery and inverter for the reference case. The variation around the average value is ±9% to ±24% [19]

4.11. Summary

The results show that for some battery technologies and conditions, batteries contribute significantly to the total energy requirement for production of PV-battery systems. Depending on the characteristics of the battery, deep discharges may reduce the cycle life of the battery.

To reduce the energy requirements of producing and transporting battery systems, the development of battery technologies should aim at higher charge–discharge efficiencies and more efficient production and transport of batteries. The battery charge–discharge efficiency has a high influence on the system energy requirements for batteries with relatively low energy requirements for production and transportation (Li-ion, VRB, and ZnBr). Service life and battery production processes are of greater importance for NiCd and PbA batteries.

The overall battery efficiency is most sensitive to changes of the charge–discharge efficiency. For batteries with relatively low energy requirements for production and transportation (Li-ion, VRB, and ZnBr), this parameter is also most important for the energy return factor.

5. Overview of design and simulation tools for PV-EES systems

The following paragraphs describe the relevant design and simulation software for PV-EES systems [[30]; [31]].

5.12. Objectives of the PV-EES system

Due to lack of optimum designing or proper sizing, a PV-EES system, is often over-sized or not properly planned or designed, which makes installation cost high. Current software tools and models can greatly simplify and shorten the design, analysis, optimization and economic planning of PV-EES systems.

5.13. Software tools

Main highlights of various software tools for PV-EES systems are reported in Table 13, while the capabilities of this software are reported in Table 14.

Table 13. Main highlights of various software tools for PV-EES systems [31]

Softwares	Developed by	Computer platform	Analysis type	Availability
HOMER	NREL,USA (1993)	Windows Visual C++	Technical analysis; economical analysis; emission analysis	Free www.homerenergy.com
HYBRID2	University of Massachusetts, USA and NREL (Hybrid1 in 1994, Hybrid 2 in 1996)	Windows XP Visual BASIC	Technical analysis; economical analysis	Free http://www.ceere.org/rerl/rerl_hybridpower.html
RETScreen	Developed by Ministry of Natural Resources, Canada in 1998	Windows 2000, XP, Vista Excel, Visual Basic, C	Financial, environmental analysis	Free http://www.retscreen.net/
iHOGA	University of Zaragoza, Spain	Windows XP, Vista,7 or 8C++	Multi or mono objective optimization using genetic algorithm	PRO version is priced & EDU version is free, http://www.unizar.es/rdufo/hoga-eng.htm
INSEL	German University of Oldenburg (1986–1991)	Windows Fortran and C/C++	Planning, monitoring of electrical and thermal energy systems	Priced www.insel.eu
TRNSYS	University of Wisconsin and University of Colorado (1975)	Windows Fortran code	Simulate transient system behavior	Priced http://www.trnsys.com/
iGRHYSO	University of Zaragoza, Spain	Windows C++	Technical analysis; economical analysis	Priced http://www.unizar.es/rdufo/grhyso.htm
HYBRIDS	Solaris Homes	Windows spreadsheet based software	Technical analysis	Unknown
RAPSIM	University Energy Research Institute Australia(1996)	Windows	Simulates performance of a range of hybrid power systems	Unknown, after 1997 any modifications are not reported
SOMES	Utrecht University, Netherlands (1987)	Windows Turbo pascal	Technical analysis; economical analysis	Unknown http://www.uu.nl/EN/Pages/default.aspx
SOLSTOR	SNL (late 1970s and early 1980s)	Windows Fortran	Technical Analysis	Not used now http://www.sandia.gov/
HySim	SNL (late 1980s)	–	Financial analysis	After mid 1990s this model is not used
HybSim	SNL	–	Cost benefit analysis	Unknown
IPSYS	–	Windows, Linux	Modeling; simulation with control strategies	Unknown www.risoe.dtu.dk
HYSYS	Wind technology group(CIEMAT), Spain	–	Sizing; long-term analysis of off grid hybrid systems	Unknown
Dymola/modelica	Fraunhofer Institute for solar energy, Germany	Windows C++	Modeling hybrid systems; financial evaluation	Unknown
ARES	Cardiff school of engineering, University of Wales, UK	Windows	Technical analysis; economical analysis	Not available
SOLSIM	Fachhochschule Konstanz (Germany)	Windows	Technical analysis; economical analysis	Not available
Hybrid Designer	Energy and Development Research Centre (EDRC), University of Cape Town, SA	Windows	Technical analysis; economical analysis	Unknown

Table 14. Capabilities of hybrid system software tools [31]

Tools	Economical Analysis	Technical Analysis	PV System	Wind System	Generator set	Storage device	Bio-energy	Hydro energy	Thermal System
HOMER	X	X	X	X	X	X	X	X	-
HYBRID2	–	X	X	X	X	X	–	–	X
iHOGA	X	X	X	X	X	X	–	X	–
RETScreen	X	X	X	X	–	X	–	–	–
HYBRIDS	–	X	X	–	–	X	–	–	–
SOMES	X	X	X	X	–	X	–	–	–
RAPSIM	–	X	X	X	X	X	–	–	–
SOLSIM	X	X	X	X	X	X	X	–	–
ARES-I &II	–	X	X	X	X	X	–	–	–
HYSYS	–	X	X	X	X	X	–	–	–
INSEL	–	X	X	X	X	X	–	–	X
SOLSIM	X	X	X	X	X	X	X	–	–
HybSim	X	X	X	–	X	X	–	–	–
Dymola/Modelica	X	–	X	X		X			
SOLSTOR	X	X	X	X	X	–	–	–	–
HySim	X	X	X	–	X	X	–	–	–
IPSYS	–	X	X	X	X	X	–	X	–
Hybrid Designer	X	–	X	X	X	X	–	–	–
TRNSYS	X	X	X	X	X	X	–	–	X
iGRHYSO	X	X	X	X	–	X	–	X	–

Several high quality tools are available at no cost. However, they do have limitations. In order to maintain ease of use and limit complexity, dimensioning tools for rough sizing like RETScreen and PV*SOL usually limit the available options for system architectures, and dispatch strategies. RETScreen provides also a comprehensive financial analysis. Simulation tools such as HOMER and Hybrid2 allow very detailed analyses. Only HOMER allows comparison between DC and AC coupled systems, the determination of optimal size of each component of the system and it provides detailed information about energy flows among various components.

Research tools, such as TRNSYS and INSEL, and the standard commercial system simulators, such as MATLAB and Dymola, allow much more flexibility in defining energy sources, system architectures, and dispatch strategies, but at the expense of considerably more effort to develop the models. For standard commercial system simulators, excepted Simplorer, the models for PV and other components must be develop by the user.

A limitation is that no direct data exchange is possible among the programs. This must be done by using (or developing) an auxiliary program or by manual input.
Another overview of simulation tools is reported in Table 15. These tools are arranged according to their availability: free (can be downloaded from the internet without fee), commercial (a fee is necessary), standard commercial system simulators (require purchase of the simulator package and development of models to meet the specific needs of the analysis desired), and internal (only available inside a specific organization or company).

The tools can be also classified in four categories: dimensioning tool, simulation tool, research tool and mi-grid design tool.

A **dimensioning tool** performs dimensioning of the system and optimise different objectives. They generally have a user interface designed to be quick and easy to use.

Simulation tools provide a detailed analysis of the behaviour of the system in relation to the input data (e.g., weather data). These tools can also provide information concerning life-cycle cost, CO_2 emissions, and sensitivity of the design to various parameters and to the deterioration of the components. They can also be used for sizing. This requires that the user correctly identify the key variables and then repeatedly run the simulation, adjusting the variables manually to converge on an acceptable sizing. Some packages automate this process.”

Research tools permit the user to modify the algorithms and the routines that determine the behaviour and interactions of the individual components. They can be programmed in a language such as Fortran, C or Pascal. Their inherent complexity limits their usefulness for sizing.

Mini-Grid Design tools assist with the design of the mini-grid electrical distribution network and model multiple generation sources within the distribution network.

Table 15. Overview of simulation tools arranged according to their availability [30]

free tools

RETScreen	dim
HOMER	sim/dim
Hybrid2	sim
Vipor *	des
Jpélec *	des

* Mini grid design

commercial tools

Off Grid Pro	dim
PVsyst	sim/dim
PV*SOL	sim/dim
Solar Pro	sim

standard commercial system simulators

Simplorer (APL)	
PowerSim	res
MATLAB/Simulink	res
Dymola	res
PowerFactory	res

internal tools

Off Grid Sizer	dim	Conergy
Sunny Island Design	dim	SMA
PVS	sim/dim	ISE
TALCO	res	ISE
Dymola	res	ISE
MATLAB/Simulink PVToolbox	res	Canmet
MATLAB/Simulink Hysis	res	CIEMAT
MATLAB/Simulink N.N.	res	ISET
PowerFactory Tool box	res	ISET

(dim: dimensioning tool, des: mini-grid design tool, sim: simulation tool, res: research tool)

An example of optimum financial planning of a renewable energy installation (solar-wind-battery-inverter) made by means of HOMER has been reported by Fulzele *et al.* [32]. A precise real time optimal cost analysis can be obtained by means of this software [33].

One of the key decisions to be made by the user when selecting a software tool concerns the desired focus of the calculations: preliminary feasibility study and general dimensioning (RETScreen), economic considerations (HOMER), a detailed technical configuration (PV-SPS, PV*SOL, PVsyst), system analysis (Hybrid2, PV-DesignPro) or detailed research (TRNSYS, MATLAB/Simulink).

HOMER is found to be most widely used tool as it has maximum combination of renewable energy systems and performs optimization and sensitivity analysis, which makes it easier and faster to evaluate the many possible system configurations.

In conclusion, the results of the system design and system simulation are dependent not only on the calculation algorithms of the program concerned, but also to a high extent on the quality of the input data, i.e. the technical knowledge and experience of the program user.

5.14. Other software tools

This paragraph describe the commercially available tools for the design of PV systems connected to the grid or in remote area. By means of this software, it is possible to accurately evaluate the solar photovoltaic energy output.

1 PV SOL

Dynamic simulation program with 3D visualization and detailed shading analysis of roof-integrated or mounted grid-connected photovoltaic systems.

2 HELIOS 3D Solarparkplanung

HELIOS 3D is a professional planning tool for utility scale PV plants. It allows shadow free placement of PV racks on a digital terrain at any geographical position and at any given date or time. The workflow supports all phases of the project process:

1) Project development: analysis and evaluation of the terrain, rate of yield.
2) Project layout: structuring of the terrain, positioning of PV racks, optimize positioning for maximum yield.
3) Project engineering: electric layout, bill of material, list of GPS coordinates, cable lists.

3 EasySolar

EasySolar is a fully functional online platform compatible with advanced EasySolar mobile apps for iOS or Android, easy to use in the office or in the field. This software provides detailed price quote section and financial analysis.

4 PVscout 2.0 Premium

PVscout is a PV-sizing software for the planning and calculation of grid-connected photovoltaic systems irrespective of manufacturer. It provides also calculations of economic efficiency.

5 PVSYST

One of the oldest photovoltaic software, developed by the University of Geneva. PVSYST is designed to be used by architects, engineer and researchers and it is a very useful pedagogical tool. It could be considered as the Swiss knife of photovoltaic software.

It is characterized by a complete database of PV panels, inverters, meteorological data and can import irradiation data from PVGIS and the NASA databases.

It provides also an economic evaluation and payback. PVsyst is able to import meteo data from many different sources and to provide results in the form of a full report, specific graphs and tables, as well as data export for using in other software.

6 Polysun

Created by SPF - Velasolaris, it is a professional sizing and simulation software of solar photovoltaic systems.

7 SOLARPRO

The software calculates the amount of generated electricity based on the latitudes, longitudes, and the weather conditions of the installation site. Simulation including the shadow influence by surrounding buildings and objects allows users to check optimal settings and module designs before system installation. The software calculates also the I-V curve of solar modules accurately and quickly based on the electric characteristics of each manufacturer's product.

8 PLAN4SOLAR PV

This software provides a comprehensive assembly and connection plan, and the relevant calculations such as inverter design, revenue forecast, and profitability calculations taking into account personal use and determining the most appropriate assembly system based on the wind and snow loads calculations in accordance with DIN 1055 and Eurocode 1 or comparable provisions at a country-specific level.

9 Solarius-PV FreeUPP

Solarius-PV FreeUPP is a software for solar photovoltaic (grid connected) design and solar PV system efficiency calculation. This PV calculator provides a graphical input also from CAD and calculation of the solar PV system efficiency rate.

10 PV F-CHART

PV F-CHART is a comprehensive photovoltaic system analysis and design program. The program provides monthly-average performance estimated for each hour of the day. The calculations are based upon methods developed at the University of Wisconsin.

11 HOMER 2

HOMER has been already presented in this section. HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. HOMER's optimization and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options and to account for uncertainty in technology costs, energy resource availability, and other variables.

12 PV-Design-PRO

PV-DesignPro v6.0 is Windows compatible software designed to simulate photovoltaic energy system operation on an hourly basis for one year, based on a user selected climate and system design.

Three versions of the PV-DesignPro program are available: "PV-DesignPro-S" for standalone systems with battery storage, "PV-DesignPro-G" for grid-connected systems with no battery storage, and "PV-DesignPro-P" for water pumping systems.

13 PV Designer Solmetric

This tool includes extensive worldwide databases of modules, inverters, and historical weather. The software is designed for residential and small commercial systems.

14 Archelios PRO

This PV software permits to calculate the PV energy produced and profitability.

15 HELIOSCOPE

This photovoltaic sizing software manages grid-connected systems up to 5MW. It provides a 45000 component library and the possibility to integrate the meteorological data in the PV solar energy calculation.

16 Solergo

This software developed by Electro Graphics Srl computes the solar PV output of a solar photovoltaic system connected to the grid. Solergo provides interesting features such as the evaluation of the polluting emissions and also an economic report and payback calculation.

17 BlueSol

BlueSol is a software for the design of photovoltaic systems in every country in the world. BlueSol is a product made with a standard Microsoft interface, easy to use.

18 INSEL

The INSEL toolbox Solar Electricity provides parameters for the simulation of all market-available PV modules and inverters.

19 Skelion

Skelion, is a sketchup's plugin to insert solar photovoltaics and thermal components in a surface. Skelion allows adding your own model.

20 Simscape™ Power Systems™

One of the products of MathWorks is Simscape™ Power Systems™ which provides component libraries and analysis tools for modelling and simulating electrical power systems. By means of these libraries and MATLAB, it is possible to simulate also a micro-grid. MathWorks already provides an example of a Simplified Model of a Small Scaled Micro-Grid on their web site [http://ch.mathworks.com]. This example shows the behaviour of a simplified model of a small-scaled micro grid during 24 hours on a typical day. The micro-grid is expressed as a power network of single-phase AC. The power sources are the power system, the solar power generation, and a storage battery. The solar power generation is a renewable energy source. A battery controller controls the storage battery, and it absorbs surplus power if there is surplus power in the micro-grid or it supplies insufficient power if there is a power shortage in the micro-grid.

21 Management Software Platform

The Management Software Platform was developed by E-sims. According to E-sims, with this platform, the producers can operate their installation (PV + storage) while optimizing its exploitation. In order to achieve that, the software platform adopts a storage model and an optimization function solver. The platform plans, checks and optimizes the storage management. It delivers the maintenance and billing services necessary to the exploitation; it handles the compatibility among electrical equipment, information systems and external services (PV forecast). The electrical architecture of the installation and the sales contract and its conditions of execution, can be configured for each site.

The platform is equipped with a Plug-in Storage and a Connected Storage Manager so that it can adapt to the specificities of each site, each contract and each user.

Plug-in Storage is a battery storage system driver. It can be used for all batteries integrating technologies such as lithium, lead and ZEBRA. It enhances the intelligence available on the storage system. It manages the short-term dynamic using the Connected Storage Manager, a scheduling software. It constructs energetic performance diagnoses and generates reports on the site.

The Connected Storage Manager optimizes the dynamic controlling of the storage system based on external events (production and consumption variation, electrical tariff, etc.). It analyses live the performance of the storage system in order to be notified on costs and profits from anywhere and to decide and correct the exploitation strategies.

22 Electric Storage Systems Simulation

Simens developed the Electric Storage Systems Simulation software. According to Siemens, it assess energy exchanges of electric storage devices in variable environment conditions. It allows modelling the electric storage systems with various complexities and features.

23 Energy Storage Toolbox

The Toolbox Speichersysteme, or Energy Storage Toolbox, was jointly developed by dSPACE, a company based in Germany that makes tools for developing electric control units (ECUs), and the Institute for Power Electronics and Electrical Drives (ISEA) of RWTH Aachen University in Germany.

According to dSPACE, this tool allows to simulate and to test batteries, supercapacitors, and other energy-storage devices according to their design and cooling systems. It provides engineers with a wide range of configuration options. In the case of lithium-ion batteries, for example, these options include battery technology and shape, the number and arrangement of storage cells, wiring topologies, and cooling systems, among others.

These configurations are used to calculate the thermal and electrical response of a simulated battery, both at the cell level and system level. It simulates thermal effects with local resolution, allowing developers to analyse different cooling strategies and to identify potential hot spots in a particular design.

Toolbox Speichersysteme was designed with special parameters for testing batteries in a simulated vehicle. The tool can also be defined via physical parameters, which are applied immediately to the simulation model. For instance, these parameters can be configured to simulate traction, energy supplies, industrial and housing technology. The batteries can be simulated either offline on a computer or in real time using a hardware-on-a-loop (HIL) simulator [http://electronicdesign.com].

24 OpenFOAM

Darcovich *et al.* [34] reported a realistic simulation of the discharge of a lithium ion battery using OpenFOAM, an open-source software. The simulation was implemented in the study of lithium ion batteries for residential power storage applications. Given that the physics is implemented on a fundamental level, it is readily adaptable to other configurations, or for considering different combinations of materials and operating conditions. Preliminary results confirm the accuracy of simulation when compared to other existing results. Making use of real household power consumption loads, they showed that a large size lithium ion battery with a 2 kW/6 kWh power capacity rating would be effective for both load levelling and cogeneration applications.

25 SIMES

SIMES is a simulator, implemented using C++, for hybrid EES (HEES) systems. This software accounts for key characteristics of various EES elements, power converters, charge transfer interconnect schemes, etc.

SIMES performs simulation for HEES systems with batteries such as Lithium-ion (Li-ion) batteries, lead-acid batteries or supercapacitors ranging from large-scale household applications to small-scale mobile device applications. SIMES was applied in the study of a household application. In this application, SIMES was used to determine the efficiency of a grid-connected HEES system in order to determine its profitability. Yue et al. reported this study in 2013 [35].

26 EnergyPlus Simulation Software

EnergyPlus is a whole building energy simulation program that engineers and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting, and plug and process loads—and water use in buildings. Some of the notable features and capabilities of EnergyPlus include:

- **Integrated, simultaneous solution** of thermal zone conditions and HVAC system response.
- **Heat balance-based solution** of radiant and convective effects that produce surface temperatures, thermal comfort, and condensation calculations.
- **Combined heat and mass transfer** model that accounts for air movement between zones.
- **Advanced fenestration models** including controllable window blinds, electrochromic glazings, and layer-by-layer heat balances that calculate solar energy absorbed by windowpanes.
- **Illuminance and glare calculations** for reporting visual comfort and driving lighting controls.
- **Component-based HVAC** that supports both standard and novel system configurations.
- **Standard summary and detailed output reports** as well as user definable reports with selectable time-resolution from annual to sub-hourly, all with energy source multipliers.

5.15. Summary

The previous list of software is far to be exhaustive. There are more and more tools coming out in order to simulate EES and HEES systems.

In conclusion, the choice of the best software is not straightforward and it has to be done in relation to the experience of the program user, the quality of the input data, the demanding simulation time, the precision and the type of output results needed (design, energy analysis, optimization, economical planning) and the offer of the software database. In fact, database are continuously updated with new battery models and technologies. This should be taken into account considering that technology is developing fast and some kind of batteries are moving quickly from the developing to the mature stage.

6. PVSyst Simulations

PVSyst simulations (using PVSyst version 6.46) were undertaken for three different locations (Bern, Seville and Örebro) in order to reproduce two cases previously reported in paragraph 3.1.2: the single house and multi-family residential both not connected to the electrical network.

The number of PV panel have been chosen in order to maximize the performance index (PR). The number of batteries have been selected in order to satisfy an autonomy respectively of the single house and of the multi-family residential of 3.7 and 3.8 days.

The battery and the PV module chosen in these simulations are respectively the Oerlikon Compact Power (voltage: 12 V, capacity: 65 Ah, technology: plaque cells) and the last generation type of PV panel (peak power: 285 Wp, silicon polycrystalline). Batteries with a capacity of 65 Ah have been chosen in order to adopt a modular configuration. The sun's path throughout the year and the daily electrical energy consumption, as well as the losses have been considered.

An overview of the main results is shown in the table below.

Locations	**Bern**	**Seville**	**Örebro**	**Bern**	**Seville**	**Örebro**
Case	Single family house			Multi-family residential		
Components	PV: poly, 3.42kWc-2.85kWc-3.135kWc, 35° Batteries: 2340 Ah, 24V Daily energy consumption: 12.08 kWh			PV: poly, 54.1kWc-45.9kWc-51kWc, 35° Batteries: 37310-37310-37635 Ah, 24V Daily energy consumption: 190 kWh		
Simulation results						
Energy production [kWh/y]	2’860	3’571	2’242	45’320	57’950	36’740
Performance index (PR) [%]	56.8	58.7	56.7	56.8	59.2	57.4
Solar fraction (SF) [%]	60.4	76.4	48.8	60.7	78.7	51
Missing energy [kWh/y]	1’746	1’041	2’259	27’300	14’820	34’050
Time fraction of unsatisfied energy needs [%]	39.1	23.8	50.7	39.1	21	48.5

The numerical simulations performed showed that the storage capacity of the investigated storage devices is limited and that currently it is difficult to cover 100% the electricity demand. In the same time, the PV production was adjusted for each location and the results showed that the maximum electricity demand is met for Seville (about 79%), while the minim is observed for Örebro.

7. Conclusions

7.16. Thermal storage

For identifying the most appropriate storage method, a simulation and a detailed study based on the characteristics of the given buildings and locations are indispensable.

Important values that need to be considered are:

- Buildings energy demand (space heating, hot water, cooling) and the load profile
- Internal heat sources (persons, electrical/electronic devices/installations),
- Buildings insulation (U-Value),
- Weather conditions (outside temperature, solar radiation).
- Insulation of thermal storage tank
- Careful matching of phase change temperature with the operating temperature of the chiller;
- Price and ageing of EES to be deployed in builings.

For the European case studies, currently water tank is the most widely spread storage method. However, it allows only short-term storage that is more appropriate for DHW. Therefore, for long-term storage in northern and middle climate zone, the most appropriate methods are pit and UTES storage. They require a minimum quantity of heating needs. Hence, it is not suitable for single houses. In southern climate zone, cooling is decisive. Thus, ice storage and UTES are the suitable storage methods for high cooling needs.

An additional short-term storage for the heating needs is PCM, integrated for example in the walls or the ceiling, and media storage media, for example in the slab. These storage methods allow stabilizing building temperature when heating needs as well as cooling needs are required.

Australian case study for solar cooling of a building application has shown that sensible storage materials can provide higher system level solar fraction despite having higher tank heat losses compared to a latent heat storage materials. This illustrates the need for careful consideration of chiller operating conditions and the phase change temperature. For example, phase change temperatures aligned with mean operating temperature requirements rather than the peak operating temperature requirements of the chiller could improve the performance of the latent heat based storage system.

7.17. Electrical energy storage

A completely state of the art of the electrical energy storage systems that are can be applied to the PV/heat pump system was performed and presented. Among these storages, the mature technology were investigated in detail.

In parallel simulation tools for EES and HEES systems were summarized. After a short analyse it came out that the choice of the best software is a compromise between several different parameters: the experience of the program user, the quality of the input data, the demanding simulation time, the precision and the type of output results needed.

Numerical simulations were performed using a PVSyst tool for two main applications using PV/heat pump systems and for three different locations. Unfortunately, the electricity needs are dissatisfied during a not negligible time fraction. If this time fraction should be minimized, an impressive amount of PV panels should be installed. Batteries with a capacity of 65 Ah have been chosen in order to adopt a modular configuration. Therefore, the amount of batteries mounted in parallel in order to obtain an autonomy respectively of the single house and of the multi-family residential of 3.7 and 3.8 days is important because of this choice.

Recent publication [38] details the importance of EES for building equipped with PV rooftop power plant. It would be interesting to investigate, in the early future, the combination of EES and thermal storage with PV.

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