

ENERGY STORAGE SYSTEMS



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Nomenclature

Greek letters

α	$\text{W/m}^2\text{K}$	heat transfer coefficient
η	-	energy efficiency of a TES
Λ	J	anergy
λ	W/mK	thermal conductivity
Λ_H	J	anergy of the enthalpy
Λ_Q	J	anergy of heat
$\dot{\Lambda}$	W	anergy flow rate
ζ	J/kg	specific exergy
ν	m^2/s	kinematic viscosity
ψ	-	exergy efficiency of a TES
ρ	kg/m^3	density
σ_S	$\text{W/m}^2\text{K}^4$	Stefan-Boltzmann constant
ε	-	emissivity (perfect black body $\varepsilon = 1$)
ϑ	$^\circ\text{C}$	temperature
ϑ_F	$^\circ\text{C}$	temperature of the fluid
ϑ_W	$^\circ\text{C}$	temperature of the wall
τ_{63}	s	response time to reach 63% of the final value
Ξ	J	exergy
$\dot{\Xi}_L$	W	exergy loss flow rate
$\dot{\Xi}_H$	W	exergy flow rate of the enthalpy
$\dot{\Xi}_Q$	W	exergy flow rate of the heat
$\dot{\Xi}_{irr}$	W	exergy loss flow rate due to irreversibilities

Latin letters

A	m^2	area
B_f	\euro	operating costs
CP	W/K	heat capacity flow rate ($\dot{m}c_p$)
c	m/s	velocity
c_p	J/kgK	specific heat capacity at constant pressure
E	J	energy
e	J/kg	specific energy
f	-	nominal number of cycles
F	As/mol	Faraday constant
g	m/s^2	acceleration of gravity = 9.81 m/s ²
ΔG_r^0	J	standard Gibbs free energy of reaction
h	J/kg	specific enthalpy
h_{amb}	J/kg	specific enthalpy of the ambient
Δh_{PC}	J/g	specific enthalpy of phase change
ΔH_r^0	J	standard reaction enthalpy
I_f	\euro	investment costs
k	$\text{W/m}^2 K$	overall heat transfer coefficient
l	m	length
L_{char}	m	characteristic length scale
m_{st}	kg	mass of storage material
\dot{m}_{in}	kg/s	mass flow at inlet
\dot{m}_{out}	kg/s	mass flow at outlet
N_{80}	-	number of cycles before the storage capacity is reduced to 80% of its nominal capacity
Nu	-	Nusselt number
p	Pa	pressure
p_{atm}	Pa	atmospheric pressure
P	W	power
P_{Charge}	W	charging power
$P_{Discharge}$	W	discharging power
Pr	-	Prandlt number
\dot{Q}	W	heat flow rate
\dot{q}	W/m^2	heat flow rate per unit area
\dot{Q}_{sum}	W	sum of heat flow rates
\dot{Q}_W	W	heat flow rate through the wall

\dot{q}_W	W/m ²	heat flow rate through the wall per unit surface area
q	J/kg	specific heat
Q_{Amb}	J, kWh	heat loss to the environment
Q_{lat}	J, kWh	latent heat
Q_l	J, kWh	heat loss
Q_{sens}	J, kWh	sensible heat
R	J/mol K	ideal gas constant
Re	-	Reynolds number
R_f	€	disassembly costs
r	m	radius
r_i	m	inner radius
r_o	m	outer radius
\dot{S}	W/K	entropy flow rate
S	J/K	entropy
s	J/kgK	specific entropy
s_{amb}	J/kgK	specific entropy of the ambient
S_{irr}	J/K	entropy created by an irreversible process
S_Q	J/K	entropy transferred with heat
ΔS_r^0	J/K	standard entropy of reaction
T	°C,K	temperature
t	s	time
T_{Amb}	°C	ambient temperature
T_{PC}	K, °C	temperature of phase change
T_i	K	temperature inside
T_o	K	temperature outside
T_W	K	temperature at the surface of a wall
U	J, kWh	internal energy
u_{in}	J/kg	specific internal energy at inlet
u_{out}	J/kg	specific internal energy at outlet
U^0	V	theoretical cell voltage
U_{cell}	V	cell voltage
V	m ³	volume
v	m ³ /kg	specific volume
W	J	work
W_E	J	electrical energy
w	J/kg	specific work
z	m	height, z-axis

Abbreviations

CHP	Combined Heat and Power
BFE	Bundesamt für Energie
EU	European Union
GDP	Gross Domestic Product
HTF	Heat Transfer Fluid
IEA	International Energy Agency
LHS	Latent Heat Storage
LT	Law of Thermodynamics
MOF	Metal-organic Frameworks
OECD	Organisation for Economic Co-operation and Development
PCM	Phase Change Material
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energies
RES	Renewable Energy Systems
SB	System Boundary
T&D	Transmission and Distribution
TES	Thermal Energy Storage
TRL	Technology Readiness Level
UTES	Underground Thermal Energy Storage
UVEK	Federal Department of the Environment, Transport, Energy and Communication
WEC	World Energy Council

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Chapter 1

Introduction: Energy Perspectives

1.1 Motivation, Typical Questions and Teaching Aims

Motivation and Typical Questions Today's Energy Systems are the reason why energy storage is of higher and higher importance. Therefore, it is important to be aware of the current energy situation and in particular of Switzerland's current situation and its plans for the future.

The following questions show the focus and the points of interest within this topic:

- Which primary and secondary energy sources are dominant in the world, Europe and Switzerland?
- What are future trends for each of these primary energy sources?
- How important are renewable sources today and in the future
- Which goals are defined by Switzerland within the Energy Strategy 2050

Teaching Aims

- I know the basis of global and national energy supply and I am able to evaluate these in the context of global changes such as climate change and national energy policy.
- I know the most important figures of energy supply and consumption by magnitude and know where detailed statistics can be found.
- I am able to describe advantages and disadvantages of renewable energies.
- I am able to elaborate on strategies how one can deal with today's complexity of energy systems.
- I can both independently and in group work elaborate on a problem and I am able to conduct complex investigations.

1.2 Important Terms

Energy reserves are well recorded energy quantities which can be obtained with current technical possibilities in an economical and legal way.

Energy resources are potential energy sources which haven't been exploited yet or might never be exploited.

Primary energy source is an energy source which can be found in the natural environment and which hasn't been subjected to any conversion (e.g. oil, sun, wind, oil, coal, etc.).

Secondary energy sources or energy carriers are forms of energy which have been produced from primary energy sources after they have undergone one or more transformations (e.g. electricity, hydrogen, etc.).

1.3 Current Energy Situation

The global energy situation is dominated by gas and oil reserves. In recent decades the use of these primary energy sources has led to significant changes in the environment. Additionally, there are more and more competitors seeking scarce raw materials, which makes creating policies to secure the supply of resources increasingly difficult.

Resources and Reserves: according to internationally accepted terminology, a distinction is made between reserves and resources of non-renewable energy. Energy reserves are well recorded energy quantities which can be obtained with current technical possibilities in an economical and legal way. The rest of the potential energy sources, which can not be exploited yet, or may never be exploited, are called resources.

Security of supply: is to be understood as, an economically portable, always adequate and uninterrupted supply of energy to satisfy demand.

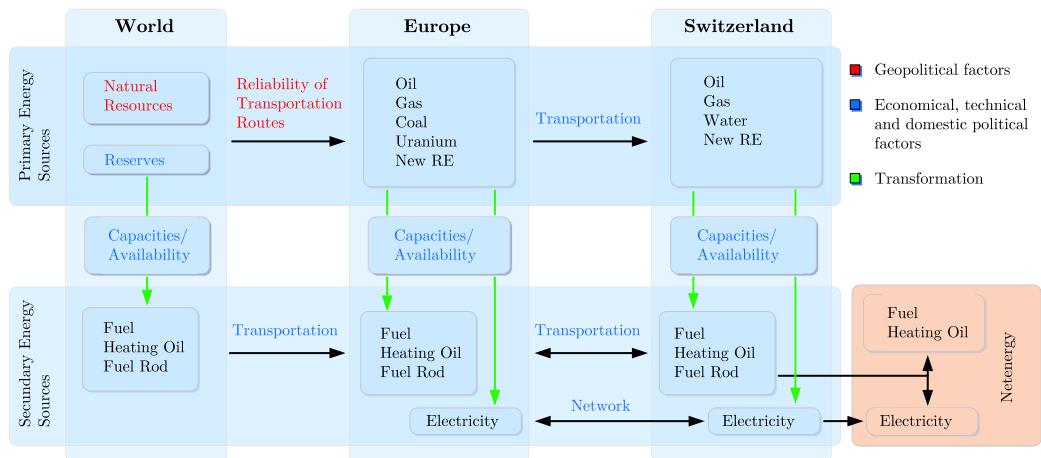


Figure 1.1: Network of primary and secondary energy sources [BFE, 2010]

Figure 1.1 illustrates the complexity of the energy supply system and displays relevant factors for the security of energy supply in the context of the entire energy supply chain. The path of energy from natural resources to consumption of useful energy can be described firstly as two levels of primary and secondary energy sources and, secondly it can geographically divided into

the areas of the world, Europe and Switzerland. Possible vulnerabilities of the energy supply, which ultimately affects the security of supply, can have geopolitical, national political, technical or economic roots.

1.3.1 Global energy supply

Worldwide, oil is the most important primary energy source, with a share of one third of the overall energy consumption, followed by coal (27 %), gas (21 %) and biomass / waste (10 %). All primary energy sources recorded in the period 1980-2008 show an increase, lead by new renewable energies (+ 642 %), albeit at a low level. With an increase of 85 %, coal has experienced a real renaissance in the last three decades. Gas consumption has seen an equally large increase of 110 %.

From 2000 to 2008 the global primary energy consumption has increased by 22 %. A view on the regions (see Figure 1.2) shows that the increase is mainly due to non-OECD countries.

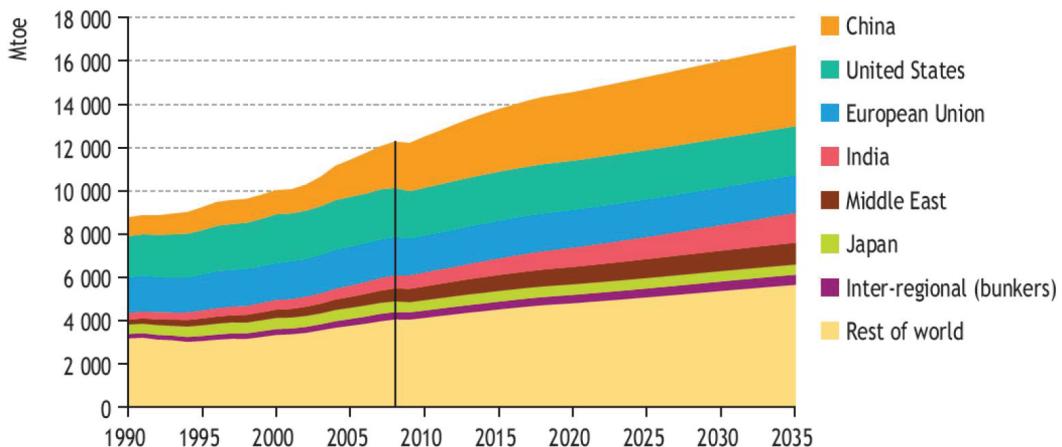


Figure 1.2: Global consumption of primary energy from 2000 to 2008 [BFE, 2010]

Oil: The world's oil reserves were given as 1,354 billion barrels in late 2009. The reserves have never been higher: they have more than doubled since 1980 and have risen by a third in the last decade. Half of the increase since 2000 is due to the opening up of Canadian oil sands. Such unconventional oil reserves (and also unconventional gas reserves) are often

found in ecologically sensitive areas, and partly under problematic conditions.

Gas: Compared to the oil reserves, the gas reserves can be judged as productive. The definitely confirmed reserves have increased steadily in recent years. At the end of 2008 they were estimated at 184 trillion cubic meters, which is about double the assessment of 20 years ago. With today's production rates, this results in a static lifetime of 58 years.

Coal: The coal resources are estimated at around 82% of all non-renewable energy resources. The reserves are about 1,000 billion tons, enough to cover the current demand for another 150 years. In contrast to conventional oil and gas, coal reserves are geographically diversified: the largest deposits are located in the United States, China, Russia, India and Australia.

Uranium: The uranium reserves are now estimated at around 5.5 Mio tons. With an annual consumption of around 66,000 tons these reserves are sufficient to cover the current demand for approximately 83 years.

Renewable Energy: Like many other studies, the WEC (World Energy Council) comes to the conclusion that the technical potential of renewable energy exceeds the world needs many times. There is no question of the potential, but the opening up of it is crucial. The IEA (International Energy Agency) assumes that independent of which scenarios are considered, renewable energies will see a strong increase by 2035.

1.3.2 Energy supply in Europe

In Europe, energy consumption increased continuously in recent decades, but has flattened since 2004. Since then the share of solid fuels (coal) decreased, while gas and renewable energy increased continuously. Since 2007, the European Council has adopted ambitious targets for 2020:

- Reduction of greenhouse gas emissions by 20% compared to 1990,
- increasing the share of renewable energy to 20% and
- improving energy efficiency by 20% compared to a development without new measures.

The intention of these goals is to make an important contribution to long-term security on energy supply. The European Parliament has continuously supported the goals, and moreover, the European Council has committed to long-term decarbonisation. The EU and other industrialized countries should reduce their CO₂ emissions by 80 to 95% by 2050.

Oil: According to the International Energy Agency (IEA) the importance of oil will decline in the EU. This is in contrast to the global trend, but similar to the three OECD regions (North America, Europe and Asia-Pacific). Thus the IEA expects that between 2008 and 2035 demand for oil will decrease by 0.5% per year on average (overall decrease of 5%).

Gas: The IEA forecasts that in the EU region between 2008 and 2035, demand for gas will see an annual increase by an average of 0.8% (17% increase in total). The EU accounts for about 38% of its gas demand with domestic production (GB, NL), while the main external gas suppliers are Russia (23%), Norway (18%) and Algeria (10%).

Coal: For coal, the IEA assumes for the EU area that the demand from 2008 to 2035 decreases with an average annual rate of 1.2% (although this is based on the estimate still on the energy policy world before the disaster in Fukushima). Overall, the decline over this period is 18%.

Electricity: The IEA forecast for the EU 2008-2035 is for an annual increase of electricity consumption by an average of 0.8% (23% increase in total). According to the IEA's baseline scenario, European electricity production in 2035 will be composed of 20% coal, 26% gas, 18% nuclear power, 10% hydro, 16% wind power and 10% other sources. Currently the European electricity grids are operating at their capacity limits. Since electricity grids are essential for the electricity supply, it is a central objective of relevant actors in the EU (and accordingly in Switzerland) to renew and to expand this infrastructure in coming decades.

1.3.3 Energy supply in Switzerland

According to the 2013 overall energy statistics from the BFE, Switzerland annually consumes 1.165 million Terajoules (TJ) of energy from primary

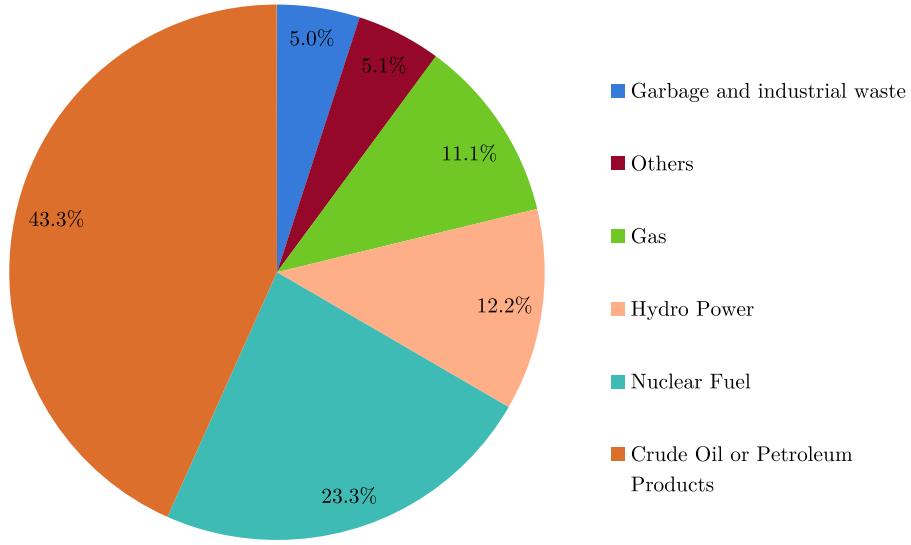


Figure 1.3: Switzerland's primary energy sources [BFE, 2013]

sources (gross consumption). The breakdown of the energy consumption is displayed in Figure 1.3.

This results in a dependence on imported sources of nearly 80%. The conversion of primary energy into secondary energy carriers is associated with losses of about 25%, so that the final consumption is 0.91 million TJ. The main secondary energy carriers for Switzerland are plotted in Figure 1.4.

With a primary energy dependence on foreign sources of around 78%, Switzerland covers only one-fifth of its consumption from domestic energy sources. This 22% is shared between hydropower, energy from wood, waste and industrial waste as well as other renewable energies (solar, wind, biogas, biopropellants, and environmental heat). The use of hydro power, with around 54.5% of the domestic share represents by far the most important energy source in Switzerland. The other renewable energy sources account for a share of around 7%. The energy consumption is almost half as high as the world average per unit of GDP and is distributed about one-third each between transport, households, industry and services. The breakdown of the energy consumption with respect to end-use can be seen in Figure 1.5.

Securing and diversifying energy imports remains a goal of Swiss energy foreign policy. This includes, among other things, the diplomatic or international legal support of private-sector projects and contracts, as Swiss energy

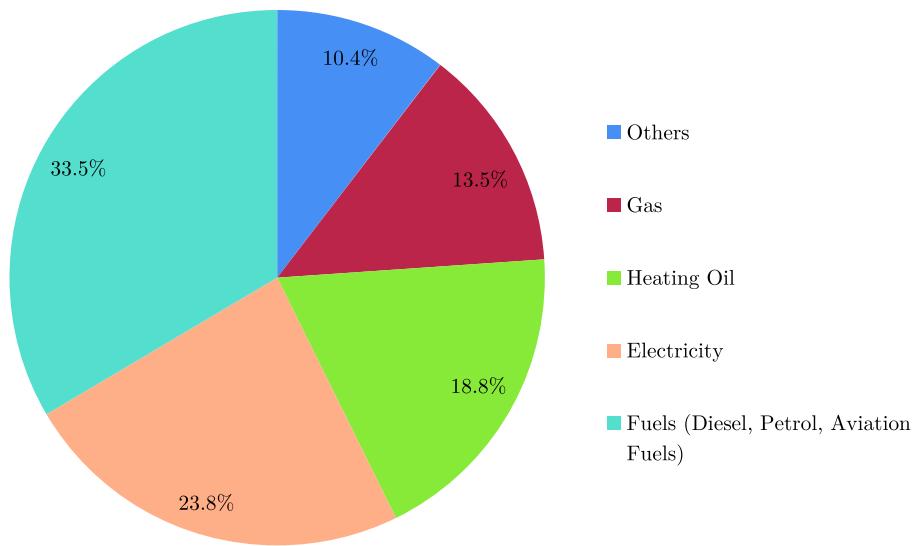


Figure 1.4: The secondary energy carriers in Switzerland [BFE, 2013]

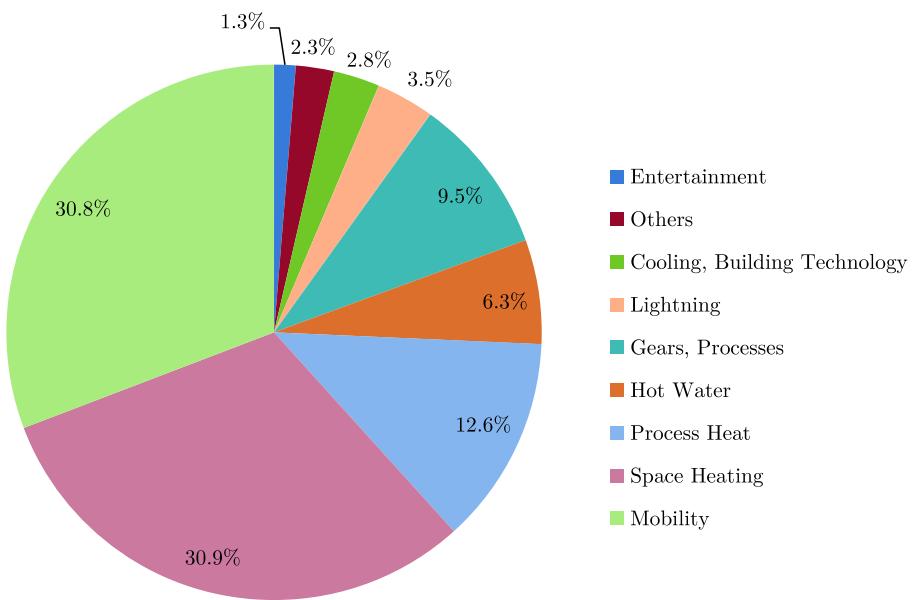


Figure 1.5: Energy consumption with respect to end-use [BFE, 2013]

imports are handled entirely by the private sector. Electricity is, however, traded in a regional European market, in which Switzerland has a significant role due to its central position in the European electricity network and the capacity for storing electricity in pumped storage power plants.

1.4 Swiss Energy Strategy 2050

Energy perspectives have been the basis of all Switzerland's energy policy choices. Since the creation of the total energy concept in the mid-1970s, these perspectives are periodically updated. The Federal Council decided on 21 February 2007, on the basis of "Energy 2035", to support its energy strategy on the four pillars of energy efficiency, renewable energies, large power plants and an active foreign energy policy. As a result of the accident in the Fukushima nuclear power facility, the Federal Council commissioned the UVEK on 23 March 2011 to update the "Energy 2035" from the year 2007 on the basis of three power supply variations

- **Going on as up to now**

Autonomous trends of the past will be observed and updated according to the current market conditions. Further on, they will be reinforced by the energy policy instruments, which are either already in force at the present time, or planned.

- **Policy measures**

The adopted measures drawn up by the Federal Council on 18 April 2012 will have been analysed, giving special consideration to their legislative basis (e.g. provisions for building standards, CO₂ emission limits for new vehicles).

- **New energy policy**

The targeted policy variant, "New energy policy", examines how to achieve the target of reducing energy-related CO₂ emissions in Switzerland to around 1.5 tonnes per head by 2050.

On 25 May 2011 the Federal Council decided to abandon new nuclear power plants (no new constructions, continuous operation of existing power plants, as long as the reliability is ensured) and confirmed the turnaround in energy policy. The contents of this turning point are:

- Reduction of the consumption of energy and electricity,
- increasing the share of renewable energies,
- ensuring access to international energy markets,

- strengthening international cooperation,
- strengthening of energy research,
- leading role of the public sector in transforming the energy supply and
- expansion and conversion of electricity grids and energy storage.

By 2050, Switzerland seeks to be a 2000-watt and a 1-1.5 ton CO₂ society (in comparison, today each and every Swiss consumes 6400 watts of power and produces around 6 tonnes of CO₂ per year). Thus, energy storage will play an important role in the framework of the Energy Strategy 2050. Since electricity (or energy) production from supply-dependent energy sources not necessarily coincide with the consumption, there is an increased need for intermediate storage of electricity (or energy).

Chapter 2

Overview of Energy Storage Technologies

2.1 Motivation, Typical Questions and Teaching Aims

Motivation and Typical Questions

Already today energy storages play an important role in many systems. Batteries are part of many applications, black start services are required for emergency cases and thermal storages are in use in almost every building in our country. This chapter gives an overview of how to structure storages and storage technologies based on various aspects:

- Where are storages located in the energy system?
- Which technology readiness level do storage technologies have?
- Which applications are present in different capacity and power scales of storages?
- How can storages be classified?
- Which set of parameters can be used to characterize storages?
- Which basic economic aspects have to be considered regarding storages in energy system applications?

Teaching Aims

- I know the most important services and benefits that storages can provide.
- I am able to discuss advantages and disadvantages of different storage technologies using the most important terms in the field.
- I am able to evaluate the benefits of different storage technologies.
- I am able to quantify economic advantages in rough estimations (similar to the case study of an ice storage in the previous lecture).

2.2 Important Terms

Ancillary Services are the services necessary to ensure reliable supply of electricity from the provider to the consumer while maintaining the integrity of the transmission and distribution grid. Such services include voltage control, frequency regulation, reserve power etc.

Arbitrage is the business model that takes advantage of the electricity price spread by storing energy when prices are low and selling it back when the prices are high.

Black Start refers to the ability of an energy supply system to start operating without the need to draw energy from the grid in order to supply the emergency power required to restore the grid operation after a failure.

Day-ahead Market is the auction-based electricity trading market, handling time slots for the next day with price calculation of every hour (or quarter hour). Switzerland is part of the Epexspot exchange market.

Energy applications are the storage technologies designed to provide a relatively moderate output power for longer periods of time (e.g. for peak shaving purposes).

Energy density is the amount of energy stored in a system per volume or mass (given in Wh/m³ and Wh/t respectively)

Frequency of discharge refers to the amount of discharges (and therefore cycles) a storage performs in a specific period of time.

Frequency regulation is the act of continuously balancing the energy supply and demand to maintain the grid frequency at normal levels and avoid damaging the grid. The management is done automatically in a minute range or shorter.

Intraday market is the electricity trading market where time-slots of the current and next day are traded. The exchange acts as an intermediary

between buyers and sellers with continuous trading of orders. Switzerland is part of the Epexspot exchange market.

Life-cycle/Lifetime costs are the overall costs of an energy storage system including the capital and operating costs for the expected lifetime of the technology.

Market deregulation the act of removing or reducing government control in a market to increase competition.

Power applications are the applications requiring high power output for a relatively short period of time (e.g. flywheel).

Power curtailment is the act of reducing electricity generation of a facility below its production capabilities to avoid excess electricity supply which could cause overload in the transmission grid.

Ramping is the increasing and decreasing of the energy output of a storage or generation unit in order to match the energy demand. Ramping can have a significant impact on the efficiency of the system.

Regulated market is a market where the government exerts a level of control on the supply and demand, for example on the price levels and on who is allowed to enter the market.

Residual load is the difference between energy supply and demand in the grid at a given moment.

Response time describes the reaction time of a storage to a charging or discharging signal.

Round-trip efficiency is the ratio of energy supplied after complete discharging of the storage divided by the total amount of energy provided for its complete charging.

Self-discharge is the portion of energy stored which is dissipated through losses during a specific storage period.

Smart Grid is an electricity network which can react to the local changes in demand and supply by utilizing digital communication systems.

2.3 Use and Benefits of Energy Storage

Energy storage technologies are systems that absorb energy, store it for a specific period of time and deliver it again when it is needed. They therefore allow for the temporal and in some cases also geographical shift of energy streams and can bridge possible gaps between supply and demand. During charging, energy is transferred to the storage with the exception of cold storage where energy is removed from the system in the charging phase. During discharging, the opposite processes takes place, with energy being absorbed by the cold storage and energy being released in all other storages.

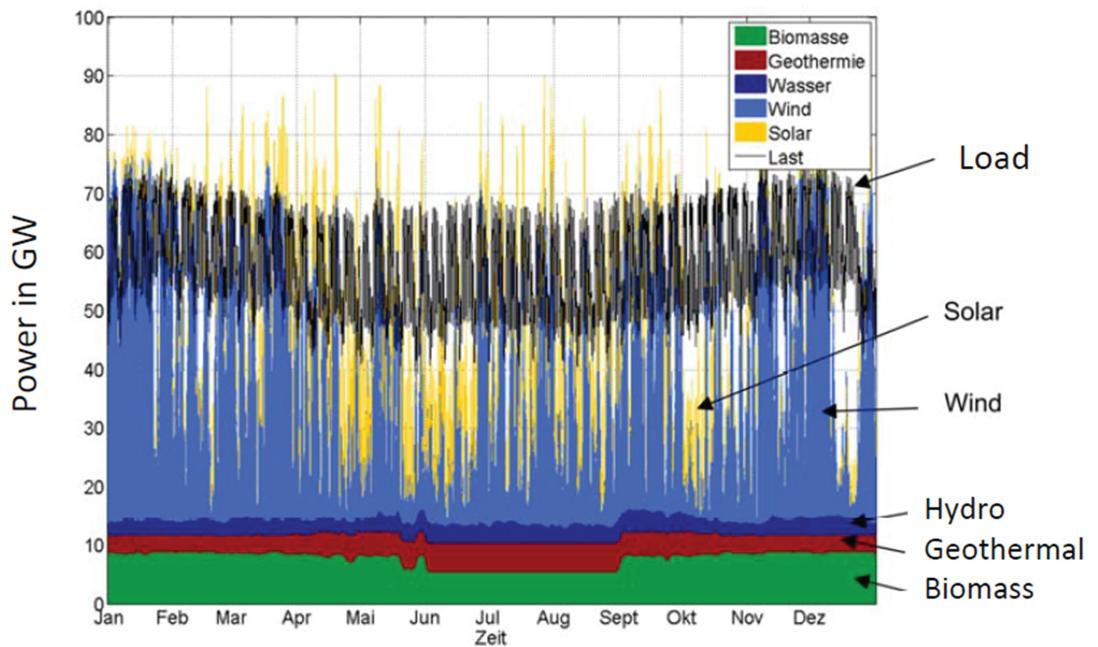


Figure 2.1: Simulated electricity supply and demand (load) in Germany for a renewable electricity scenario (source: Sterner et al., 2010).

As seen in Figure 2.1 a large share of stochastic RE sources in the grid would lead to strong fluctuations of energy supply and result in creation of residual load (see Figure 2.2). This discrepancy between supply and demand occurs in different time scales (seconds, hours, months) and can result to grid instability and failures. Storage technologies can help bridge these supply and demand differences and can thus play a crucial role in assisting the implementation of new RE technologies.

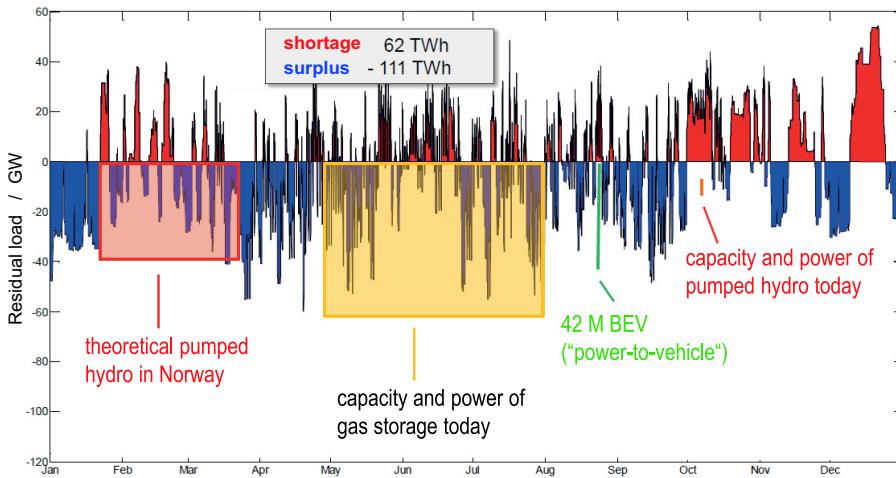


Figure 2.2: Difference between electricity demand and supply (=residual load) for the scenario shown in Figure 2.1 (source: Fraunhofer IWES, 2010).

As seen in Figure 2.3 many storage technologies are in a mature or near-mature phase but most are still in a basic research or R&D phase. The maturity level of technologies is often described by the Technology Readiness Levels (TRL) which are defined as:

- TRL 1: Capture and presentation of the operating principles.
- TRL 2: Definition of the concept and respective applications of the technology.
- TRL 3: Analytical and experimental proof of the most important functions.
- TRL 4: Validation of main system components in the laboratory.
- TRL 5: Validation of a similar laboratory model in a relevant environment.
- TRL 6: Validation of a representative model or prototype system, tested in a relevant environment.
- TRL 7: Demonstration of a similar prototype-system in a relevant environment.
- TRL 8: Completion of the final-system and qualification through tests and demonstration.

- TRL 9: Successful demonstration of the final-system operation at all operation points.

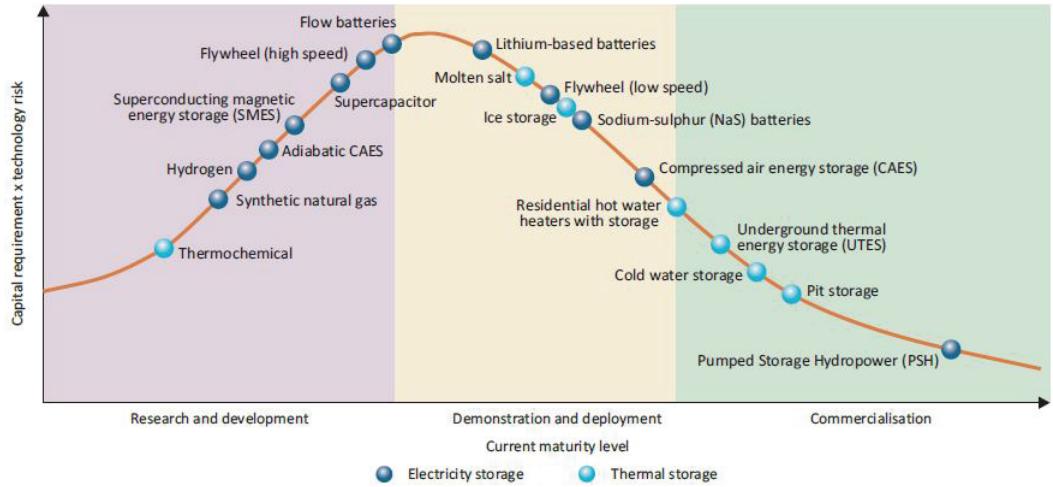


Figure 2.3: Maturity levels of relevant storage technologies [IEA, 2014]

2.3.1 Storage benefits and services

The value of energy storage technologies depends on their ability to provide useful services to the energy system. These services and their applications are often classified in three categories: (i) grid system applications (ii) end-user applications and (iii) RE applications. Not all storage technologies can provide every service. Storage services require different specific technical properties (power output, capacity etc.) and a combination of various storage technologies has to be employed to cover all of them. A list of the most important services is provided below [IEA, 2014], [Pieper, 2011]:

(a) Arbitrage or storage trade is the act of purchasing and storing energy when the power prices are low, to resell it when energy prices are high. It can be performed with units installed both on the transmission and on the distribution grid. This service is profitable only when the spread between peak and off-peak prices is sustainably large enough. An example of the electricity price fluctuations in the power exchange market is shown in Figure 2.4. The minimum allowable spread is related to the round-trip efficiency of the storage technology by:

$$\eta > \frac{\text{valley price}}{\text{peak price}} \quad (2.1)$$

There are two main challenges associated with this service: (i) it is hard to predict the price developments in advance and (ii) it has the tendency to self-destruct (if a critical amount of players enter the market, the price spread will cease to exist).

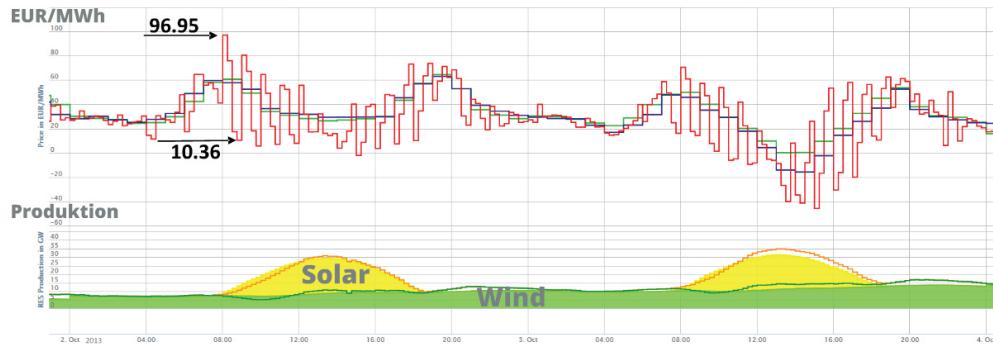


Figure 2.4: Electricity price fluctuation in the EpeXspot power exchange market as it developed on the 2nd and 3rd of October 2013 in Germany.

(b) Black-start refers to the emergency power required to restore the grid operation after a failure. All highly developed grids need to have the ability to provide the black-start power in case of emergencies which is arranged in the form of contracts between grid operators and the service providers. Standard power plants are normally not capable to provide this service because they require to draw electricity from the grid in order to initiate their operation. The major source of revenue for this service is not the energy/power provided but the commitment to provide the necessary energy when an emergency occurs. In the case of energy storage black-start service can be combined with other services to increase revenue and is particularly interesting for storage technologies which are not fully discharged under normal operation (e.g. batteries). A conventional method to provide black-start services is via diesel generators.

(c) Energy Balancing. The electricity generation and demand in the grid need to be equal at all times. Consequently the grid operators need to have methods to balance out possible fluctuations, both on the load side (e.g. unexpected increase or decrease of demand) and on the generation side (e.g. stochastic energy sources, unexpected technical failure of power plant). The employed technologies can provide positive balancing energy (supplying power when the demand is too high) or negative balancing energy (drawing power when generation is too high). This service has three sources of revenue:

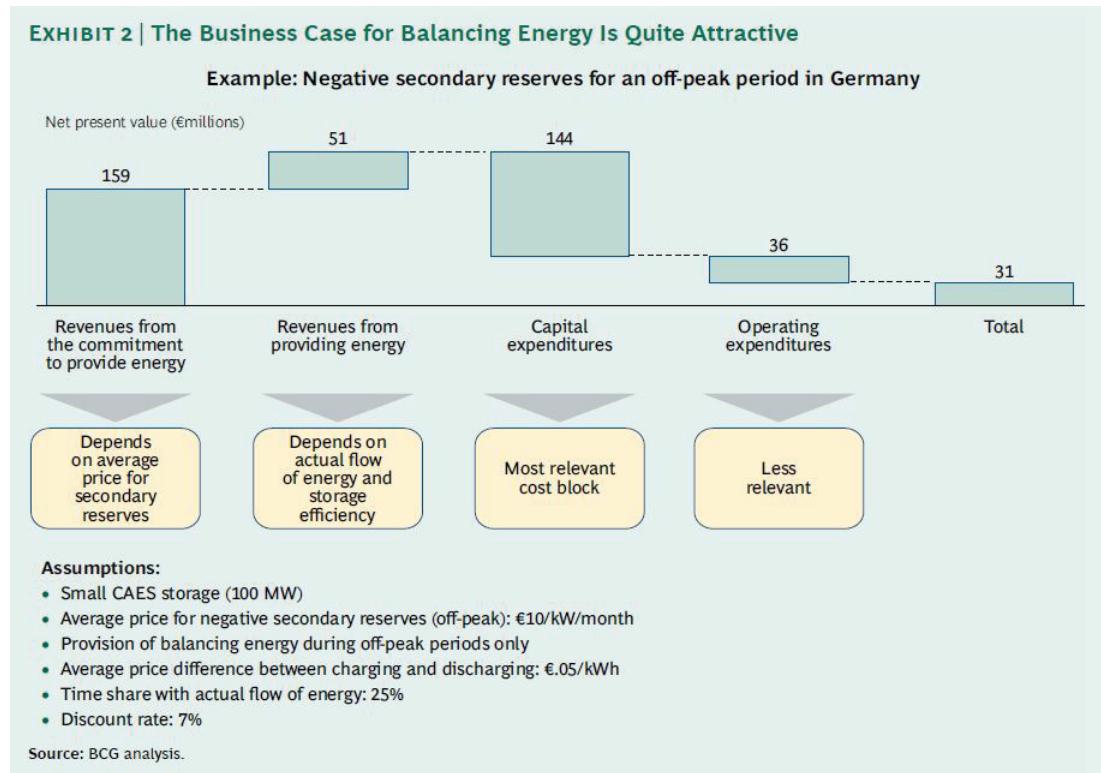


Figure 2.5: Example of business case for negative secondary reserves for an off-peak period in Germany [Pieper, 2011].

(i) price paid up-front to guarantee the provision/consumption of energy when it is required, (ii) price paid for the energy supplied/consumed itself and (iii) price paid for the time the grid operator used the energy-balancing unit. Because of the high technical and reliability standards required, electricity tariffs are higher for technologies providing balancing services. The electricity price increase with the decrease of the response time. Based on the response time the balancing reserves can be divided to: (i) primary (reaction within milliseconds), (ii) secondary (reaction within 30 seconds) and (iii) minute reserves (reaction within minutes). A case study for balancing energy business case can be seen in Figure 2.5. A more detailed listing of the different energy balancing services is given below.

- **Spinning and non-spinning reserve** refers to the extra capacity reserved to be used in the case of an unexpected loss of a generation resource. A spinning reserve refers to increasing the power output of an already operating generator and has a faster response time (< 15 min.). A non-spinning reserve is disconnected capacity which can be-

come available with a slower response time (>15 min).

- **Demand shifting and peak reduction.** In order to reduce the maximum energy demand (peak) and achieve a better match between energy demand and supply, storages can be charged during off-peak times (e.g. charge hot storage for building heating) and deliver the energy during peak times.
- **Frequency regulation** is the continuous shifting of supply and demand to ensure the grid frequency is kept within the tolerance bounds. Frequency management is often done automatically and requires storages with response time in the order of one minute.
- **Load following** is the second continuous electricity balancing mechanism which manages fluctuations in the minute and hour range. The control can be both automatic or manual.
- **Voltage support** is the absorption or release of reactive power in the transmission or distribution level of the grid, to maintain the voltage levels under normal operating conditions.

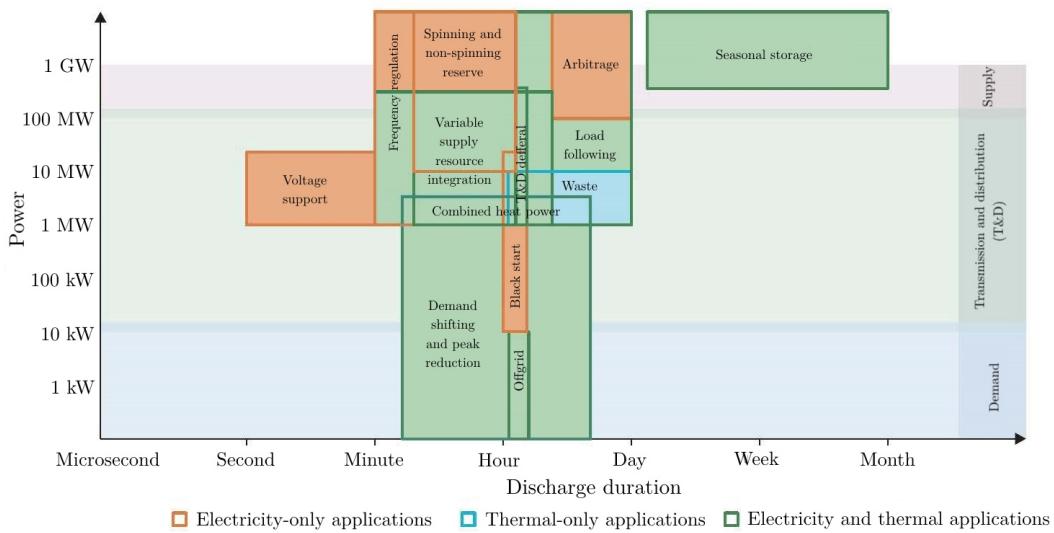


Figure 2.6: Summary of typical storage applications and services provided by electrical and thermal energy storages sorted by power output and discharge duration [IEA, 2014]

- (d) **Transmission and distribution (T&D) congestion relief and infrastructure investment deferral** is the shift of demand and supply

to relieve congestions in the grid and to avoid the need to expand the T&D grid. An expansion of the T&D grid is necessary when the increase in demand causes the load to exceed the maximum allowable load during peak hours. The cost of such an extension can be very high, depending on the required upgrade. To avoid this costly operation, a suitably sized storage can be installed near the load which is charged during off-peak hours and discharged during peak hours.

Application/Service	Output (electri-city, thermal)	Size (MW)	Discharge duration	Cycles (typical)	Response time
Seasonal Storage	e, t	500 to 2000	Days to months	1 to 5 per year	Day
Arbitrage	e	100 to 2000	8 to 24 hours	0.25 to 1 per day	> 1 hour
Frequency regulation	e	1 to 2000	1 to 15 minutes	20 to 40 per day	1 minute
Load following	e, t	1 to 2000	15 minutes to 1 day	1 to 29 per day	< 15 minutes
Voltage support	e	1 to 40	1 second to 1 minute	10 to 100 per day	Millisecond to second
Black start	e	0.1 to 400	1 to 4 hours	< 1 per year	< 1 hour
Transmission and Distribution (T&D) congestion relief	e, t	10 to 500	2 to 4 hours	0.14 to 1.25 per day	> 1 hour
T&D infrastructure investment deferral	e, t	1 to 500	2 to 5 hours	0.75 to 1.25 per day	> 1 hour
Demand shifting and peak reduction	e, t	0.001 to 1	Minutes to hours	1 to 29 per day	< 15 minutes
Off-grid	e, t	0.001 to 0.01	3 to 5 hours	0.75 to 1.5 per day	< 1 hour
Variable supply resource integration	e, t	1 to 400	1 minute to hours	0.5 to 2 per day	< 15 minutes
Waste heat utilization	t	1 to 10	1 hour to 1 day	1 to 20 per day	< 10 minutes
Combined heat and power	t	1 to 5	Minutes to hours	1 to 10 per day	< 15 minutes
Spinning reserve	e	10 to 2000	15 minutes to 2 hours	0.5 to 2 per day	< 15 minutes
Non-spinning reserve	e	10 to 2000	15 minutes to 2 hours	0.5 to 2 per day	< 15 minutes

Figure 2.7: Characteristics required from storages in order to perform specific services [IEA, 2014]

(e) Integration of variable supply resources. As already discussed, a number of challenges can arise from a large penetration of RE sources to the energy system mainly due to their intermittent and stochastic nature. Energy storage technologies provide resources for the energy system to deal with these challenges, ensure reliable supply of energy and avoid curtailment.

(f) Off-grid energy access The challenges related to RE penetration become more critical to off-grid application where the buffering quality

of an energy network is not present. Energy storage can support the implementation of RES in such systems and allow for the supply of clean, affordable and reliable energy supply in developing and/or remote regions.

(g) Increase self-consumption. In cases of local energy production (e.g. residential PV), the issue of increasing self-consumption is coming up often in the context of increasing autarchy and decreasing cost (avoiding paying the grid tariff). In such cases the storage would be charged when the energy generation exceeds the demand and discharged when the demand exceeds the generation.

2.3.2 Storage application examples

It is important to distinguish between energy storage applications and storage benefits. A benefit can be a revenue stream, a cost reduction or an avoided cost. A technology implemented in a specific application can provide several benefits. Some important storage application which can provide one or more of the aforementioned services/benefits is presented below:

(a) Industrial peak shaving aims at flattening the power demand (reducing power peaks) of the industrial site and is of particular interest for applications characterized by a strong variation of energy demand throughout the day. The storage unit is typically designed to charge during off-peak hours and supply the power during peak-demand hours (see Ice Storage case study). The revenue streams for a storage in such applications can result from: (i) reducing cost by consuming lower-priced, off-peak electricity (ii) reducing investment cost by decreasing equipment size (e.g. heat pump, chiller, cooling tower etc.) and (iii) decreasing grid-connection fees which are proportional to the maximum power consumed.

(b) Seasonal storage refers to the storage of heat, cold or electricity for periods up to several months. It can be broadly defined as a system that stores energy during one season to deliver it in another season and therefore reducing seasonal fluctuations in supply and demand. A typical example is storing heat during the summer in an underground thermal energy storage (UTES) using solar collectors to release it in the winter when the solar irradiation is lower but the heat demand is higher.

(c) **Waste heat utilization** refers to the storage of waste heat which can't be utilized at the time of its production and would normally be rejected to the environment. The energy stored can be used at a later point when it is needed. A typical example is storage of process heat for batch industrial processes, where the process heat from one batch can be stored to heat the next batch, drastically increasing the process efficiency.

(d) **Combined heat and power (CHP)**. CHP plants produce fixed ratios of electricity and heat which typically don't match the corresponding energy demands. Thermal and electricity storages can be implemented in such plants to bridge the gap between supply and demand.

A summary of services and applications of electrical and thermal storage technologies is presented in Figure 2.6 with respect to typical power output ranges and discharge durations. The corresponding characteristics that the storage technologies need to possess in order to perform these services and applications are presented in Figure 2.7.

2.4 Types of Energy Storage

There is a wide range of energy storage types. The main categorization followed in this script is based on the energy output: (i) electricity, (ii) thermal energy and (iii) fuel. Especially in the case of electricity storage, the form of energy input differs from the form of the energy stored and can also differ from the storage output. An overview of the important storage systems is presented in Figure 2.8, classified based both on the form of energy output, and on the form of energy stored. More information on the specifics of each technology will be presented in the next chapters.

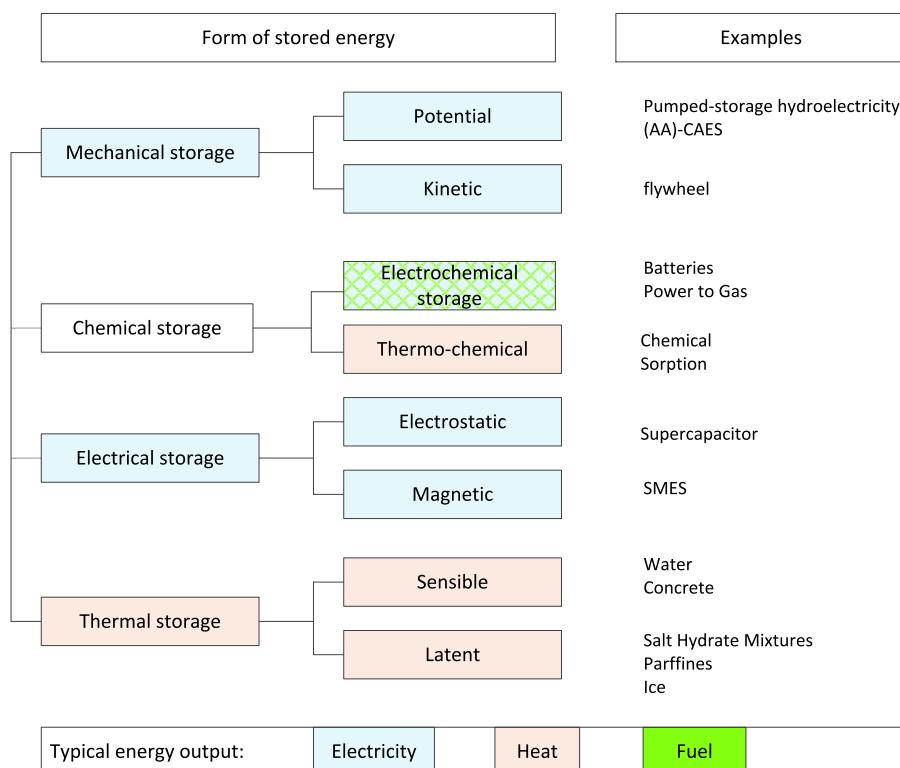


Figure 2.8: Overview of Energy storage systems based on energetic output and energy storage method [Hafner, 2014]

2.5 Energy Storage Classification

Several classification methods are used to structure and compare energy storage systems. The main classification methods are presented below:

- **Energy output.** As discussed in the previous chapter, storage systems are often classified according to the form of output energy. We distinguish between (i) electrical storages (storages that supply electricity), (ii) thermal storages (storages that supply heat) and (iii) fuel. This classification has already been presented in section 2.4 and depicted in Figure 2.8 where blue boxes represent the storages providing an electrical output, red boxes the storages providing a thermal output green boxes the storages providing fuel.
- **Form of stored energy.** Storage systems can also be classified according to the energy form which is used for the storage itself irrespective of their energy input or output. An example of this classification can be seen in Figure 2.8.
- **Location on energy system.** As presented in section 2.6, energy systems can be separated in centralized and decentralized (distributed). Centralized electricity storages are larger-sized systems located in the supply and T&D section of the grid whereas decentralized are the smaller scale electricity storages that are located on the demand side and are connected at the edge of the network. For thermal energy storages the term centralized refers mostly to large storages (hundreds of kW to MW) connected to a heating/cooling network (e.g. district heating and cooling), while the term distributed refers to smaller units that are placed on the demand side of the energy system.
- **Power output.** According to BFE, energy storage systems can be classified according to their power output in micro-storage, small-scale storage, medium-scale storage and bulk storage. The proposed classification in connection to charge/discharge duration and possible applications is shown in Figure 2.6.
- **Response time.** This classification applies mostly to electricity storage systems where response time is often crucial to the type and quality of services a storage can provide (see Figure 2.7). The response time ranges from milliseconds to days.

- **Storage period** refers to the period during which the energy remains stored before it is released and is related to the discharge frequency. Short term storages (second-minutes) are mostly applied to grid-stabilization applications whereas longer term (hours-seasonal) for energy shifting applications. Longer term storage systems are required to have very low self-discharge and high energy densities (e.g. thermochemical, chemical).

2.6 Levels of Energy Storage Application

Storages can be deployed on different levels of the energy system. The European electricity network is divided in 7 levels, including the supply, transmission and distribution or demand (end-use) level (see Figure 2.9).

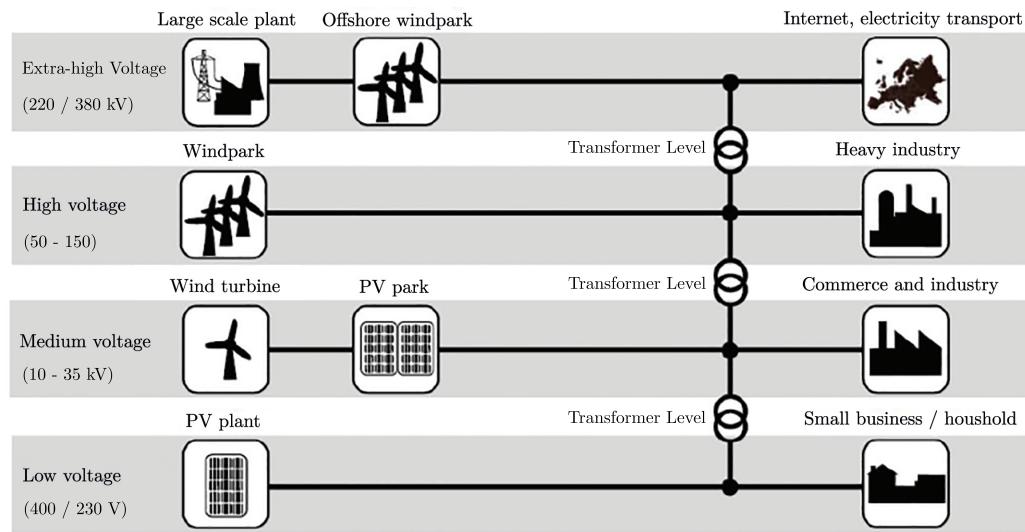


Figure 2.9: Levels of electricity grid [Hafner, 2014].

Electricity storages can be theoretically employed across any of the aforementioned levels. An example of energy storage deployment in different locations can be seen in Figure 2.10. The optimal location for each energy technology depends on the type services it is designed to serve. Centralized storages are typically connected to the high-voltage transmission grid (>110 kV). They have the advantage of "self-balancing" because they combine a number of different energy sources/loads with different fluctuation patterns. Decentralized applications on the other hand are typically positioned in the distribution grid and are only connected to a small number of sources/sinks. A big advantage of decentralized storage units is that they are positioned near the source/load so they reduce the required grid capacity. A list of the most important storage technologies along with their main characteristics and typical locations in the energy system is presented in Figure 2.11.

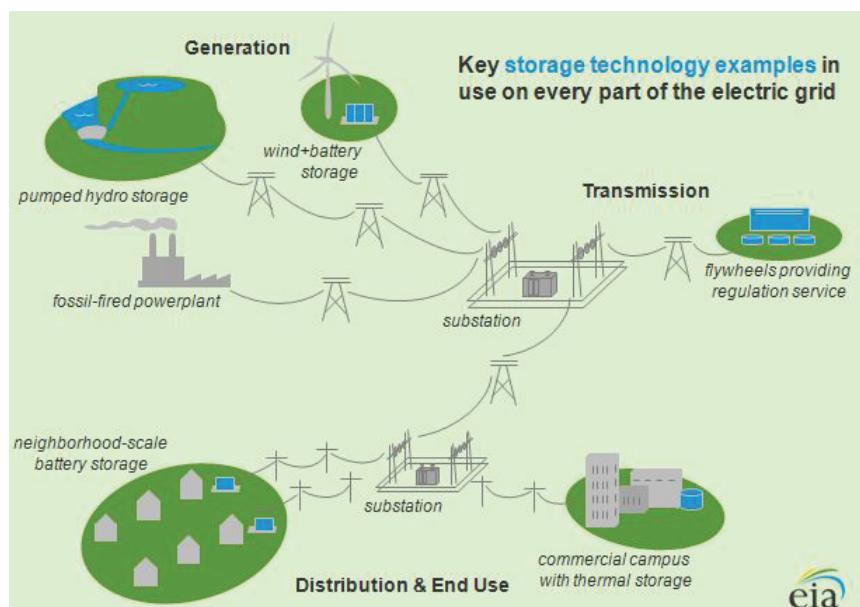


Figure 2.10: Examples of storage deployment in different levels of the energy system (from:<http://www.eia.gov>, "Electricity storage: Location, location, location....and cost")

Technology	Location	Output	Efficiency (%)	Initial investment (USD/kW)	Primary application	Example projects
PSH	Supply	Electricity	50 - 85	500 - 4 600	Long-term storage	Goldisthal Project (Germany), Okinawa Yanbaru Seawater PSH Facility (Japan), Pedreira PSH Station (Brazil)
UTES	Supply	Thermal	50 - 90	3 400 - 4 500	Long-term storage	Drake Landing Solar Community (Canada), Akershus University Hospital and Nydalen Industrial Park (Norway)
CAES	Supply	Electricity	27 - 70	500 - 1 500	Long-term storage, arbitrage	McIntosh (AL, USA), Huntorf (Germany)
Pit storage	Supply	Thermal	50 - 90	100 - 300	Medium temperature applications	Marstal district heating system (Denmark)
Molten salts	Supply	Thermal	40 - 93	400 - 700	High-temperature applications	Gemasolar CSP Plant (Spain)
Batteries	Supply, demand	Electricity	75 - 95	300 - 3 500	Distributed/ off-grid storage, short-term storage	NaS batteries (Presidio, TX, USA and Rokkasho Futamata Project, Japan), Vanadium redox flow (Sumitomo's Densetsu Office, Japan), Lead-acid (Notrees Wind Storage Demonstration Project, USA), Li-ion (AES Laurel Mountain, USA), Lithium Polymer (Autolib, France)
Thermochemical I	Supply, demand	Thermal	80 - 99	1,000 - 3,000	Low, medium- and high-temperature applications	TCS for Concentrated Solar Power Plants (R&D)
Chemical-hydrogen storage	Supply, demand	Electrical	22- 50	500 - 750	Long-term storage	Utsira Hydrogen Project (Norway), Energy Complementary Systems H2Herten (Germany)
Flywheels	T&D	Electricity	90 - 95	130 - 500	Short-term storage	PJM Project (USA)
Supercapacitors	T&D	Electricity	90 - 95	130 - 515	Short-term storage	Hybrid electric vehicles (R&D phase)
Superconducting magnetic energy storage (SMES)	T&D	Electricity	90 - 95	130 - 515	Short-term storage	D-SMES (USA)
Solid media storage	Demand	Thermal	50 - 90	500 - 3,000	Medium temperature applications	Residential electric thermal storage (USA)
Ice storage	Demand	Thermal	75 - 90	6,000 - 15,000	Low-temperature applications	Denki University (Tokyo, Japan), China Pavilion project (China)
Hot water storage (residential)	Demand	Thermal	50 - 90	...	Medium temperature applications	Peak demand reduction (France), TCES (USA)
Cold water storage	Demand	Thermal	50 - 90	300 - 600	Low-temperature applications	Shanghai Pudong Int. Airport (China)

Figure 2.11: List of important storage technologies with characteristics and typical locations in the energy system [IEA, 2014]

2.7 Indicators for Energy Storage Characterization

Categories	Key Figures	Description
Technical Potential (qualitative)	Grid Location: central, decentralized or local	Refers to typical the application of storage technology.
	Characteristics: Power- or Energy-Application	Refers to typical the application of storage technology.
	Energy carrier: elec., heat, fuel	Consideration of the system connection point of storage.
	Power output: micro- and small scale storages, medium-scale and bulk storages.	Typically classification: micro \leq 100 kW, small 0.1 - 10 MW, medium 10 – 100 MW, bulk 100 MW – 1 GW (Hewicker, et al., 2013).
	Operating cycle: continuously, intermittent or cyclically	Refers to typical the application of storage technology.
Technical properties (quantitative) ¹	Energy density: $\frac{E}{m}$ [Wh/kg]; $\frac{E}{V}$ [Wh/l]	Specifies the amount of energy a storage technology can store under nominal working conditions and with respect to a reference unit (volumetric or gravimetric).
	Power density charging: $\frac{P_{charge}}{m}$ [W/kg]; $\frac{P_{charge}}{V}$ [W/l] Power density discharging: $\frac{P_{discharge}}{m}$ [W/kg]; $\frac{P_{discharge}}{V}$ [W/l]	Specifies the power output that a storage technology can provide under nominal working conditions and with respect to a reference unit (volumetric or gravimetric).
	Round-trip efficiency (cycle efficiency) $\eta_R = \frac{\text{Energy feed}}{\text{Energy intake}} [\%/\text{cycle}]$	Describes the average of the storage specific transformation losses of the self-discharging over time and under nominal working conditions. One cycle consists of a charging and a discharging process (minimal load to nominal load to minimal load).
	Self-discharging rate: $\frac{\Delta E}{\Delta t \cdot E_N}$ [%/d]	Refers to the stored energy lost over a time period without discharging. The value of the nominal load is based on a specific system. The self-discharging rate determines the reasonable storage period.
	Response time: time constant of the power-step-response $\tau_{63 \text{ load}}$ [s]; $\tau_{63 \text{ discharge}}$ [s]	Describes the reaction time of a storage to a charging or discharging signal. Starting from power = 0, τ_{63} indicates the time after which 63% of the nominal power is reached. The quantity describes for example the suitability of a storage for reserve power services (Schlipf, Scherer, & Haller, 2012, S. 4)
	Nominal number of cycles per year f [1/y]	Basis to calculate the operating costs and lifetime of a specific system.

Categories	Key Figures	Description
	Lifetime: Number of possible cycles N_{80} .	Number of charging /discharging cycles (minimal to maximal load). The lifetime is reached, once only 80% of the storage's nominal capacity can be reached.
Politics, Institutions	Dependency of individual suppliers	Qualitative description of possible dependencies and shortages during the acquisition of required subsystems and resources.
Environment	Potential to endanger the environment Availability of the resources for all stages	Considering all stages (from manufacturing to disposal). Qualitative description considering all stages (from manufacturing to disposal).
Society	Endangerment of persons	Qualitative description.
Economic aspects	Fixed investment costs: I_f [€] Variable investment costs: $\frac{\Delta I}{\Delta E}$ [€/kWh]; $\frac{\Delta I}{\Delta P}$ [€/kW] Fixed annual operating costs: B_f [€/y] Variable annual operating costs: $\frac{\Delta B}{\Delta E}$ [€/kWh/y]; $\frac{\Delta B}{\Delta P}$ [€/kW/y]	Fix one-time investment per system at year zero. One-time variable costs per energy or power unit at year zero. The total investment costs I are approximated as: $I = I_f + \frac{\Delta I}{\Delta E} \cdot E + \frac{\Delta I}{\Delta P} \cdot P$ Fix per unit and year, incl. annual reserves for renewal Variable costs per energy or power unit with nominal amount of annual cycles, incl. annual reserves for renewal. Total annual operating costs: $B = B_f + \frac{\Delta B}{\Delta E} \cdot E + \frac{\Delta B}{\Delta P} \cdot P$
	Fixed disassembly costs: R_f [€] Variable disassembly costs: $\frac{\Delta R}{\Delta E}$ [€/kWh]; $\frac{\Delta R}{\Delta P}$ [€/kW]	One-time fix per unit at end of lifetime (for disassembly time of several years counted back to the last year of operation), not discounted One-time variable costs per energy or power unit at end of lifetime (for disassembly time of several years counted back to the last year of operation). The total costs of disassembly result from the sum: $R = R_f + \frac{\Delta R}{\Delta E} \cdot E + \frac{\Delta R}{\Delta P} \cdot P$
Technology readiness	Maturity level 1-6: See Section 2.4.	Description of the state of technology of a specific project. Classification by the maturity level [Cleantech, 2014, S. 15-17]

Figure 2.12: Indicator system to characterize and compare storage technologies.

2.8 Economic Aspects

Even though there are many cases where storage technologies are cost competitive, most of them are still too expensive compared to conventional energy solutions. A methodology that can be used to assess the value of a storage technology is shown in Figure 2.13. This includes the calculation of the storage lifetime costs in relation to its performance and its environmental impact. Additionally, the possible sources of revenue that the technology can provide have to be identified. The revenues have to be quantified for different possible applications under different operation scenarios. The determined value of a storage in a specific application has to be compared with the value alternative technologies that could provide the same services in order to identify the optimal technology to be implemented in the specific application.

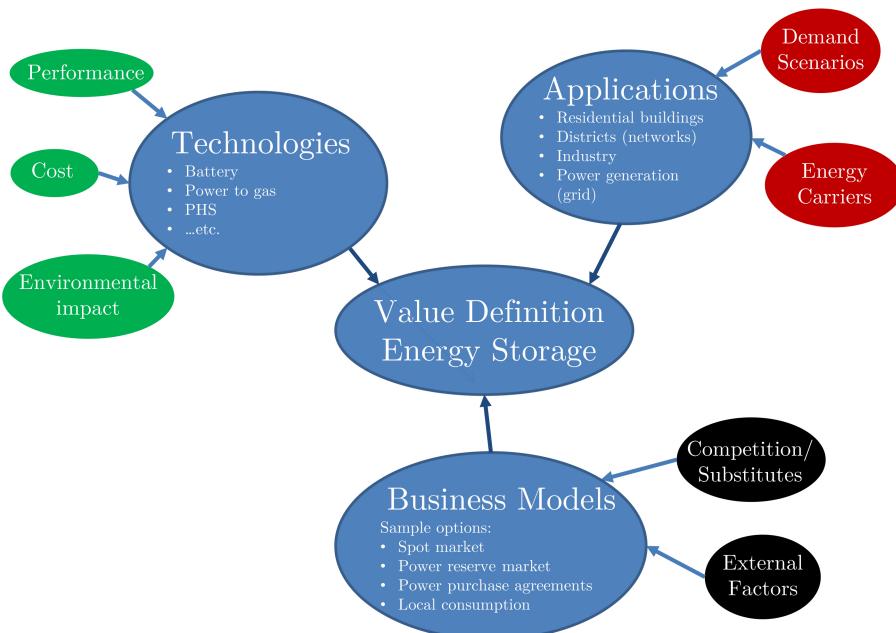


Figure 2.13: Value definition methodology for energy storage systems.

Cost calculations.

Similarly to any other system, energy storage technologies become financially interesting when total gains during the products lifetime, exceed the total expenses. For a more complete representation and a more thorough comparison between energy technologies, the costs for the entire life-cycle are often considered. The costs of a system is based on investment or capital costs, operation and maintenance costs, efficiency, cycle life, parasitic energy

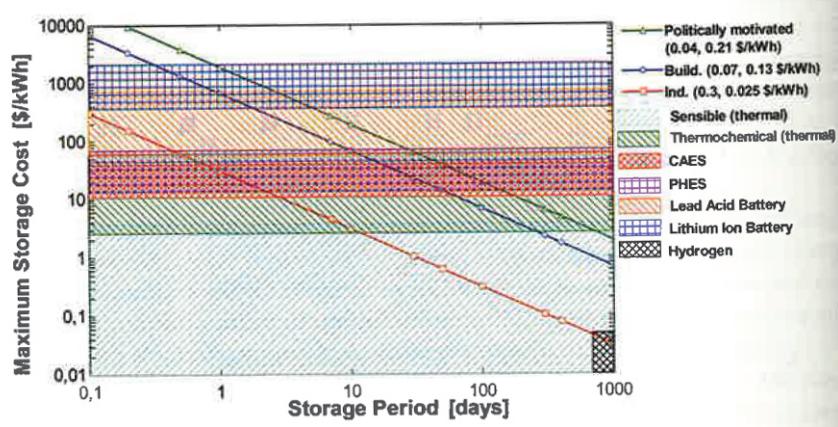


Figure 2.14: Maximum acceptable storage costs as a function of storage period including estimated cost for various storage technologies [D. Stolten, 2013].

requirements and replacement costs. The results are often presented in cost per unit capacity (CHF kWh^{-1}) or cost per unit power (CHF kW^{-1}). The cost-breakdown and calculation of individual costs can be found in Figure 2.12. Assuming a number of operation hours per year, annual costs can be recalculated as revenue requirement which is the amount in cents kWh^{-1} that an energy provider would need to charge for each kWh to cover all the costs related to owning and operating the system. The latter consideration is not appropriate for power quality storages which are only bound to operate a few minutes per year. The maximum acceptable storage costs as a function of the storage period including the estimated cost for various storage technologies is depicted in Figure 2.14. A similar graph considering acceptable costs of thermal storages in Switzerland is shown in Figure 2.15.

Storage benefits.

Benefits are financial gains that result from the usage of the storage. They can come in the form of a revenue stream, a cost reduction or a cost that can be avoided by using a storage. A detailed list of services and benefits can be found in section 2.3. An example of estimations related to the profitability of various benefits for a battery storage is shown in Figure 2.16. A storage unit in a specific application can however serve more than one services which can result to several revenue streams, increasing the profitability of the storage system. An example of storage costs compared to benefits from individual services as well as with stacked benefits is presented in Figure 2.17.

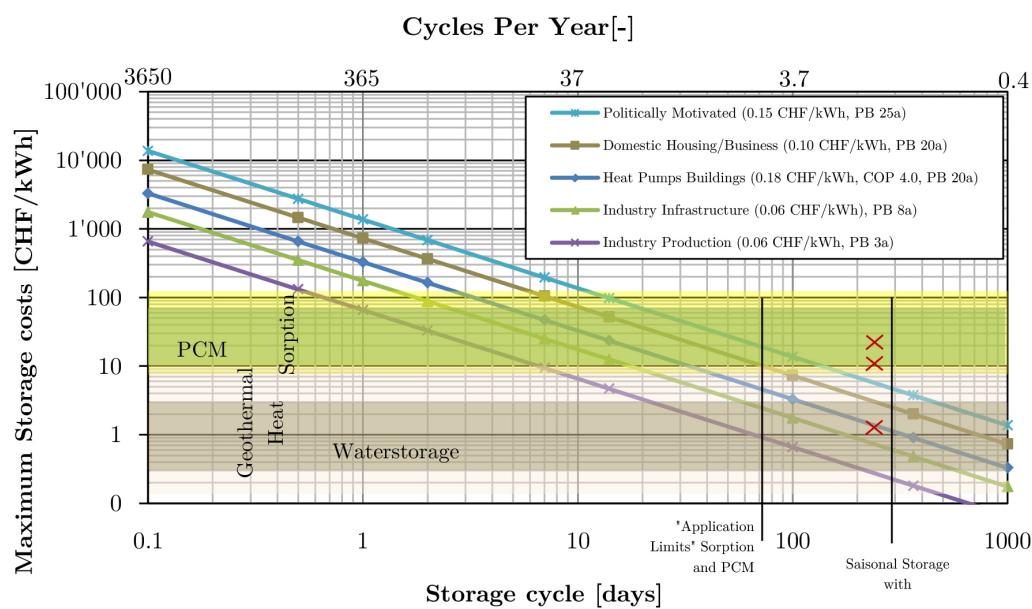


Figure 2.15: Maximum acceptable thermal storage costs as a function of storage period for Switzerland.

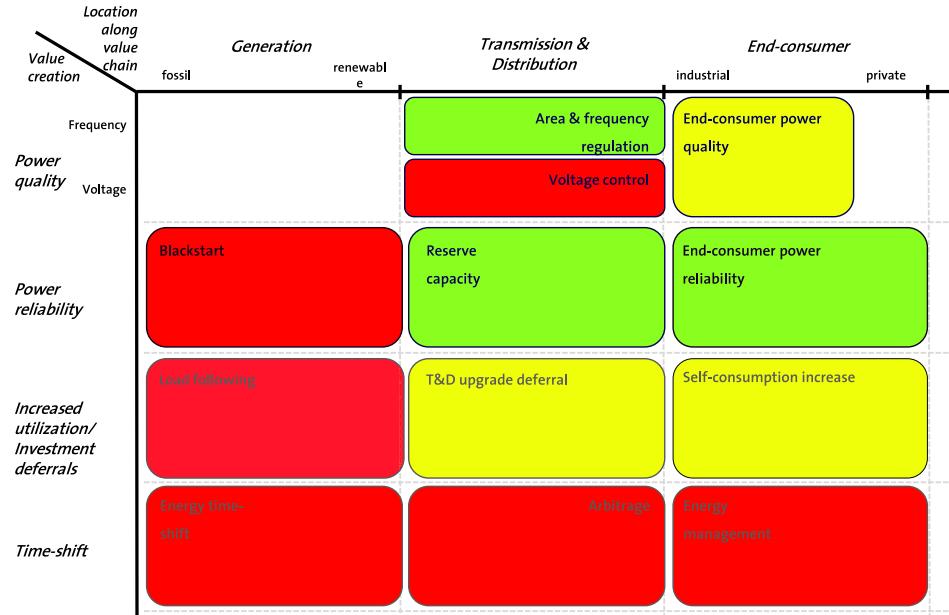


Figure 2.16: Estimations of profitability of various battery benefits. Green indicated an already profitable case, yellow a close to profitable case and red a very unprofitable case (source: Presentation of B. Battke at Frontiers of Energy Research).

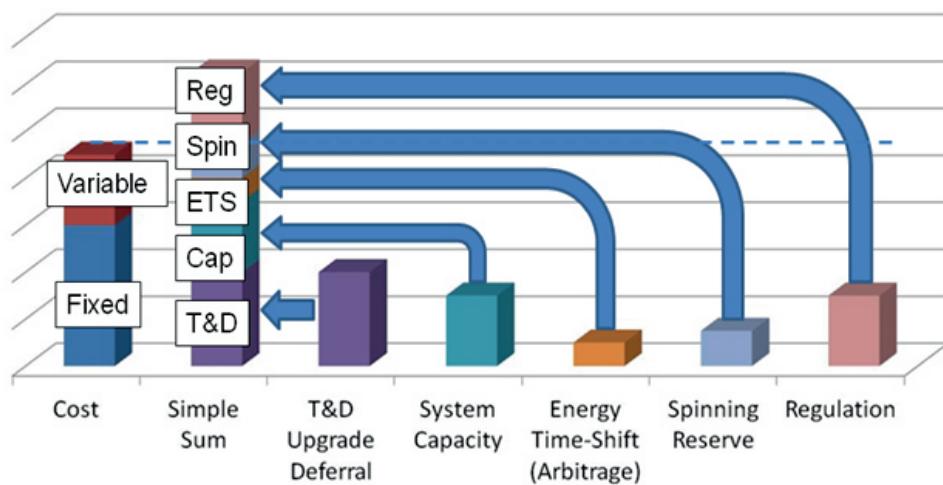


Figure 2.17: Storage costs compared with individual grid service benefits and stacked benefits [EPRI, 2013].

Chapter 3

Energy Storage in Fuels

3.1 Motivation, Typical Questions and Teaching Aims

Motivation and Typical Questions

The power-to-gas (P2G) concept offers the prospect of storing excess electricity on the grid-scale by converting electricity to hydrogen or synthetic natural gas. Key technologies in this scenario are electrochemical water splitting (electrolysis) and CO₂ methanation.

- What scale of energy and power are we talking about if electricity is to be generated largely by fluctuating renewables?
- How much storage capacity is required?
- What is P2G, how does it work ?
- How does P2G compare to other technologies ?
- Gas storage options
- What are mobility concepts in a renewable energy scenario

Teaching Aims

- I am familiar with the implications of electricity supply largely based on renewable sources
- I know the idea behind P2G and how it is anticipated to be implemented
- I know the basics of water electrolysis
- I know the basics of CO₂ methanation
- I can name key advantages and shortcomings compared to other storage technologies

3.2 Important Terms

Power-to-Gas (P2G) is an energy storage concept whereby excess electricity is converted to hydrogen or methane (synthetic natural gas).

Residual Load is the difference between electricity demand and supply in the grid at a given point in time, it has the unit of power.

Electrolysis is the electrochemical splitting of water into hydrogen and oxygen.

Methanation is the reaction of carbon dioxide or carbon monoxide and hydrogen to generate methane.

Gas-to-liquid (GTL) is a refinery process to convert natural gas or other gaseous hydrocarbons into longer-chain liquid hydrocarbons, e.g., gasoline or diesel fuel.

3.3 Water Electrolysis

One of the key technologies in the P2G concept is the water electrolysis. The electrochemical splitting of water is a non-spontaneous and endothermic reaction driven by energy input:



which has a standard reaction enthalpy ΔH_r° of 286 kJ/mol (higher heating value, HHV, of hydrogen). This total energy has to be provided as ΔG_r° (237 kJ/mol) in the form of electrical energy and $T \cdot \Delta S_r^\circ$ (49 kJ/mol at 298 K) as heat. The theoretical cell voltage is given by

$$U^\circ = -\frac{\Delta G_r^\circ}{zF} = -1.23V \quad (3.2)$$

where z is the number of electrons transferred per formula unit ($z = 2$), and F is the Faraday constant, the charge of 1 mol electrons ($F = 96,485$ As/mol). Typically, however, positive voltage values are used for practical reasons. In a technical cell, driving the water electrolysis reaction at a significant rate, i.e. at current densities on the order of 1 A/cm², requires an overpotential to compensate for electrode, ohmic and mass transport losses. The electrical energy W_E used for electrolysis is then given by $W_E = z \cdot F \cdot U_{Cell}$, where U_{Cell} is the operating voltage of the cell. $U_{Cell} - U^\circ$ is the overpotential. The voltage efficiency of the water electrolysis reaction is the ratio of the HHV of the produced hydrogen and the electrical energy input W_E :

$$\eta = \frac{\Delta H_r^\circ}{W_E} = \frac{\Delta H_r^\circ}{zFU_{Cell}} = \frac{1.48}{U_{Cell}} \quad (3.3)$$

For example, if the electrolysis cell is operated at 1.8 V, the voltage efficiency is 82 %, at 2.0 V the voltage efficiency is 74 %. In addition, there is the faradaic efficiency, which accounts for losses of the produced H_2 and O_2 , for instance through permeation through the membrane, and systems-related efficiencies, which originate from the fact that the balance of plant components, such as pumps, also require electricity, which adds to the total electricity used to produce, say, 1 kg of hydrogen.

There are various types of water electrolyzers and technical implementations: the alkaline cell, the polymer electrolyte cell, and the solid oxide cell (table

Table 3.1: Characteristics of different types of water electrolysis cell

Cell Type	T [°C]	Electrolyte	Comment
Alkaline	40 - 90	aqueous KOH	mature technology, low current density
Polymer electrolyte	20 - 100	proton exchange membrane	high investment cost, high current density, compact design
Solid oxide	700 - 1,000	oxide ceramic	laboratory stage, low W_E input

3.1). These technologies have rather different characteristics. The alkaline cell has been used for over 100 years for industrial hydrogen production, it is therefore a mature technology with low investment cost, owing to the nickel-based catalysts used in the electrodes. Large installations of the MW type have been in operation since the 1960s. The lifetime of this type of cell is 10 years and more. A downside, however, is the use of corrosive aqueous KOH electrolyte and the low current density (several 100 mA/cm²). The polymer electrolyte (PE) cell was developed from the early 1970s onwards. It is an acidic type cell that uses a proton exchange membrane (such as Nafion®) as electrolyte. The acid environment necessitates the use of noble metal catalyst, Pt on the negative, H₂ electrode, and Ir-oxide on the positive, O₂ electrode, which leads to high investment costs. Yet the thin (150 - 200 μm) electrolyte membrane leads to small ohmic losses and allows an operation at much higher current densities of 1 to 2 A/cm². The stack is therefore considerably smaller compared to an alkaline stack for a desired H₂ production rate. The lifetime of PE type electrolyzers is, at the present time, lower than that of an alkaline electrolyzer. Due to the use of a membrane electrolyte, the PE cell can be operated at differential pressure, which is of interest, for example, if hydrogen is the main product. The solid oxide electrolysis cell (SOEC) technology is at the laboratory scale. Owing to the high operating temperature, less electricity input is required to drive the water splitting reaction. This is a consequence of thermodynamics and a decreasing theoretical cell voltage with increasing temperature, because of the fundamental relationship

$$\Delta G_r^\circ = \Delta H_r^\circ - T \cdot \Delta S_r^\circ \quad (3.4)$$

At 1,000°C, the theoretical cell voltage for the water splitting reaction is 0.82 V. A typical operating cell voltage in an SOEC is 1.2 V, which means that the reaction takes place with an electrical efficiency of $\eta = 1.48V/1.2V = 123\%$.

Since 1.2 V is below the thermoneutrale cell voltage of 1.48 V, heat input is required. Therefore, at the operating temperature of an SOEC, a larger share of the total energy required to split water has to be provided by heat, which makes this technology attractive to use in combination with processes where high quality waste heat at a temperature of 700 °C or more is readily available.

New developments in water electrolysis cells involve improvements in the traditional alkaline type cell, for instance by adopting a zero-gap design approach, which leads to lower ohmic losses and allows the operation at higher current densities. Furthermore, the advantages of the alkaline (non-noble metal catalyst) and polymer electrolyte (compact design, absence of corrosive electrolyte) cell are sought to be combined in the alkaline membrane water electrolysis cell. The challenges here are obtaining anion exchange membranes with high conductivity and chemical stability. Currently, these properties are much inferior compared to those of proton exchange membranes.

3.4 Methanation of CO₂

The second technology of high importance in the P2G concept with "gas" meaning SNG is the methanation reaction (Sabatier reaction):



which is an exothermic reaction ($\Delta H_r^\circ = -165\text{kJ/mol}$). The obtained methane can be injected, after drying, into the natural gas network. Therefore, the entire storage capacity for natural gas can be tapped in this manner. An important question in this scenario is: where does the CO₂ for the methanation reaction come from? In general terms, a number of CO₂ sources suggest themselves. One of the options is to use CO₂ produced in coal power plants. If pure oxygen is used for the burning of the coal (oxy-fuel process), the flue gas primarily consists of CO₂ and resource-intensive separation of CO₂ and N₂ is not required. Although the CO₂ is originally produced from fossil feedstock, its reuse in the P2G process would lead to an overall improved CO₂ balance, since it is used twice to generate useful energy (power, heat). An abundant source of CO₂ could be ambient air. However, its low concentration of around 400 ppm requires a cost- and energy-intensive process based on absorption in alkaline solutions to enrich CO₂. A third option is to use CO₂ that is produced in industrial processes as waste, whereby the associated cost and energy depends on the exact nature of the process. Ideally, the CO₂ containing gas stream needs as little treatment as possible to be compatible with the methanation reaction. An attractive source of CO₂ in this context is biogas. The primary gaseous products from the fermentation process in a biogas plant are CH₄ and CO₂, typically at a ratio of close to 1:1. The mixture of CO₂ and CH₄ can be directly fed to the methanation reactor, where the CH₄ in the gas stream is increased close to 100 % due to the additional CH₄ produced from CO₂ and H₂.

Example:

16 kW_e (electric) are used to electrolyze water, which, at a process efficiency of 75 %, yields a H₂ gas stream with energy content equivalent to 12 kW_{th} (thermal). A biogas (CH₄ / CO₂) feedstream with 15 kW_{th} energy content (due to the CH₄) is fed, together with the H₂, to the methanation reactor, which has an efficiency of 83 %, yielding CH₄ with an energy content of 10 kW_{th}. The energy content of the methane injected into the natural gas network is therefore 15 kW_{th} + 10 kW_{th} = 25 kW_{th}.

3.5 The implication of P2G

The design of the water electrolysis and methanation reaction in a P2G plant will undoubtedly be strongly affected by the nature and availability of the CO₂ source, such as the size of the installation, i.e., whether it is a centralized or decentralized installation. In any case, considerations of conversion efficiency in each of the steps and the overall process is essential. Table 3.2 provides an overview of different storage technologies with round-trip efficiencies and buffering capacities. Batteries, offering attractive efficiency, are suitable for short term storage only. For storage capacities on the order of weeks, pumped hydro has been used traditionally, for which the efficiency is comparable to some of the battery technologies. As discussed before, however, pumped hydro is limited by the geography and availability of suitable sites. Compressed air storage relies on underground cavities, such as salt or rock caverns, aquifers and abandoned mines, for storage. Although P2G offers large (theoretical) storage capacities, the anticipated round-trip efficiency, i.e., the losses experienced from power-to-gas-to-power, is rather poor, in particular in the case of power-to-SNG, where about 2/3 of the original energy is lost. The improvement of the efficiency of the individual processes is therefore of paramount importance to the technology.

Table 3.2: Electricity storage characteristics of different technologies

Technology	Round-trip efficiency [%]	Buffering capacity
L-ion battery	80 - 90	hours
Na/S battery	75	hours
Redox flow battery	75	hours
Pumped hydro	75	days, weeks
Compressed air	65 - 70	days, weeks
P2G (H ₂) ^a	34 - 44	weeks, months
P2G (CH ₄) ^a	30 - 38	weeks, months

^are-electrification at an efficiency of 60 %

There are a number of issues that one is led to consider in the framework of an energy supply largely based on renewable sources and P2G. One important question is: how will individual mobility change in such a scenario? There are a number of trajectories with different vehicle technologies. Battery electric vehicles (BEV) have already begun to appear on the market. They are emission-free vehicles (locally), yet investment costs are high and

range limited. In addition, the cycle-life of batteries is critical. Also, the electricity mix used to charge the battery is key to judge the environmental friendliness of the technology. Fuel cell electric vehicles (FCEV) running on hydrogen start to be offered commercially this year (2015) by Toyota. They offer a higher driving range, yet investment costs are even more significant here. In addition, a hydrogen refueling infrastructure is largely nonexistent today. The same considerations regarding the electricity mix to produce the H₂ today have to be made here. Internal combustion cars are likely to be around for several decades. In principle, vehicles with gas engine can be fuelled with SNG derived from natural sources, such as a biogas plant, as mentioned above, or methane produced in a P2G process.

Example:

A pilot plant for the production of SNG via P2G for fueling cars is the Audi e-gas has been put into operation in Werlte, Lower Saxony (Germany). 6 MW electricity are used to produce H₂, which is then reacted with CO₂ from a local biogas plant to yield 300 Nm³ SNG per hour. Taking the heating value of CH₄ (11 kWh/Nm³), this corresponds to 3.3 MW_{th}, the efficiency of the process is therefore 55 %.

In addition, liquid fuels can be made from methane via the Fischer-Tropsch process (gas-to-liquid process) to obtain hydrocarbons with chain length similar to that of gasoline. In this way, today's vehicles could be used without adaptations. This route is sometimes also referred to as "Power-to-Liquid" or "Power-to-Fuel". Although "green" methane or liquid fuels would be used in this scenario, local pollution from the combustion in the internal combustion engine would result.

In conclusion, it is valuable and helpful to review the opportunities and challenges one faces regarding the (grid-scale) implementation of P2G technology. The key arguments are compiled in Table 3.3.

Table 3.3: Non-exhaustive list of opportunities and challenges of P2G

Opportunities	Challenges
use of existing natural gas infrastructure	low round-trip efficiency
huge storage capacity for long-term storage	need cheap electricity if SNG is to be competitive to fossil SNG
methane = established fuel / chemical diversified mobility scenario	centralized vs. decentralized production suitable CO ₂ source

3.6 Concluding remarks

Energy supply in the future is likely to be based on an increasing share of renewables. Considering electricity supply, fluctuating sources, such as wind and solar power, are anticipated to make up sizeable contributions. This leads to a number of challenges. First, for balancing supply and demand installations for storage on the TWh or tens of TWh scale will need to be deployed. P2G offers the prospect of exploiting the natural gas network as energy storage medium. The type of CO₂ source will probably dictate whether centralized or decentralized P2G plants are targeted. In any case, the transmission capacity of the electricity grid needs to be significantly increased to bring electricity from the place of generation to the place of use or storage. A major shortcoming of P2G is the poor turnaround efficiency of only around 35 %. Can the concept be economical? How will legislation steer the energy and electricity industry with benefits and taxation ? As to the role of scientists and engineers, their mandate is to improve the different technologies to maximize efficiency, performance and lifetime, and develop solutions that can be competitive and marketable.

Chapter 4

Thermal Energy Storage

4.1 Motivation, Typical Questions and Teaching Aims

Motivation and Typical Questions More than 50% of our energy consumption is dedicated to heating and cooling applications. Therefore, thermal storage has always played an important role, especially in building. Within the energy turnaround thermal storage is one of the key elements as well due to low costs e.g. compared with battery storage. This chapter gives an overview of the possibilities to store heat and cold. Additionally, it explains critical factors of storing heat and cold via sensible, latent or chemical storage types. Additionally, the basis of designing and calculating thermal storages are given. Typical questions are:

- How can heat and cold be stored?
- Which temperature levels are of interest and which storage types are used.
- Which applications are present in different capacity and power scales of storages?
- How can thermal storages be classified?
- Which materials can be used to store heat and cold.
- Which applications of thermal storages are typical today and where are chances for the future?
- Which challenges do new technologies and applications show?
- How can storage capacity and power of the thermal storage be calculated?
- How can heat and cold be transferred to charge and discharge the storage?

. Teaching Aims

- I know application example of thermal energy storages in different temperature ranges
- I am able to classify thermal storages by their type of heat transfer

- I am able to discuss advantages and disadvantages of different thermal storage technologies using the most important terms in the field.
- I am able to perform energy and exergy balances of storages.
 - I am able to analyse stratified storages
 - I can calculate the resulting power of thermal storages based on heat transfer calculations
 - I am able to numerically solve dynamic changes in sensible and latent heat storage.

4.2 Important Terms

Absorption is a process in which a gas or a liquid enters another bulk phase (solid, fluid or gas).

Adsorption. Adhesion of a gas or a liquid on a surface,

Anergy. Energy that can't be converted into work (e.g. thermal energy at environmental conditions).

Aquifer Thermal Energy Storage. Thermal energy storage which uses the sensible heat of groundwater. Used for seasonal energy storage.

Borehole Thermal Energy Storage. Energy storage system in which heat is transferred to the soil using boreholes. The energy is later retrieved by pumping cold liquid trough the boreholes.

Charging. Input of heat in a high temperature storage unit or input of cold in a low temperature storage unit.

Discharging. Extraction and delivery of heat from a high temperature storage unit or extraction and delivery of cold from a low temperature storage unit.

Dispatchability. The ability of a power-producing facility to provide required amounts of power.

Dissociation reaction. Reaction in which a molecule is split in smaller parts (i.e. radicals, ions).

Endothermic process is a process during which the system absorbs heat from its surroundings.

Enthalpy. Internal energy plus the product of pressure and volume ($H = U + pV$).

Exergy of a system of interest with respect to a reference system is the maximum theoretical work that can be extracted as the two systems interact until they reach equilibrium.

Exothermic reaction is a process during which the system releases heat to its surroundings.

Ideal gas. An ideal gas is a theoretical gas composed of many randomly moving point particles that do not interact except when they collide elastically. It is a good approximation for many common gases at room temperature.

Incompressible fluid. Fluid with a constant density.

Liquidus temperature denotes the temperature above which a material is completely liquid.

Latent Heat is the energy absorbed/released by a material when it undergoes a phase change at constant temperature.

Packed-bed storage. Thermal energy storage system in which the heat is

stored in a porous medium.

Phase Change Material. A substance with a high heat of fusion which is used to store thermal energy.

Reversible reactions are chemical reactions where the formed products, under suitable conditions, can react back to form the initial reactants. **Solidus temperature** denotes the temperature below which a material is completely solid.

Sorbent. A sorbent is a material used to absorb or adsorb liquids or gases.

Sorptive. Substance that gets absorbed or adsorbed by a sorbent.

Stratification refers to a temperature distribution of fluid layers in a storage tank characterized by a vertical density and temperature gradient.

Sensible Heat is the heat whose transfer to or from a body or system results in a temperature change.

Sorption is a chemical or physical process through which a substance takes up or binds another substance.

Thermocline is a temperature gradient in a body, observed between two layers of different uniform temperatures.

4.3 Introduction

4.3.1 General information

Thermal Energy Storage (TES) technologies are systems which store heat or cold to deliver it at a later point for heating, cooling and electricity production applications. The three simple processes taking place in TES systems are described in Figure 4.1 as: (i) charging (input of heat or cold in the storage unit), (ii) storing (idle phase of storage unit) and (iii) discharging (delivery of heat or cold from storage unit). Since approximately half of the energy consumed in Switzerland is used for heating and cooling applications (See Figure 1.5), implementation of TES can offer the necessary flexibility in the future energy system and can thus play an important role in Switzerland's energy transition.

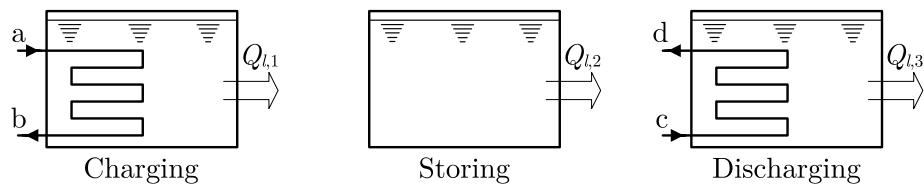


Figure 4.1: The three stages in a simple TES process, including thermal losses to the environment [Dincer and Rosen, 2002].

There are three types of TES based on the storage form/medium: (i) sensible TES, where the energy is stored by heating or cooling of a liquid or solid storage medium, (ii) latent TES, where the storage medium (called Phase Change Material(PCM)) undergoes a phase change during the charging/discharging storing the energy as latent heat and (iii) thermo-chemical where a reversible chemical reaction or sorption process takes place during charging/discharging. The classification of TES based on the form of stored energy and the type of the relevant process can be seen in Figure 4.2. Sensible TES is the most common of the three TES types as it is a relatively simple and low cost technology. Latent and thermo-chemical TES are less mature, more complicated technologies, with higher investment costs, but have the potential of exhibiting higher energy densities and round-trip trip efficiencies than sensible TES. Figure 4.3 summarizes the important performance parameters of the three TES types.

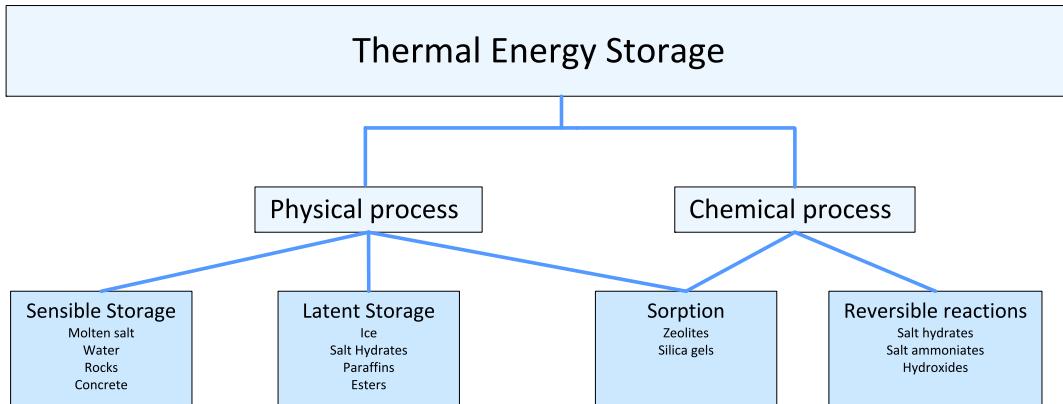


Figure 4.2: Classification of TES types based on process type and form of stored energy.

TES types	Energy density [kWh/t]	Power [MW]	Round-trip efficiency	TRL	Investment costs [CHF/kWh]
Sensible	10 - 50	0.001 - 10	50 - 90	7 - 9	0.12 - 12
Latent	50 - 150	0.001 - 1	75 - 90	2 - 4 (ice: 8)	12 - 60
Thermo-chemical	120 - 250	-	75 - 100	1 - 2	12 - 120

Figure 4.3: Important performance parameters of the three types of TES (values based on [Hafner, 2014])

4.3.2 Temperature levels

TES systems can be grouped in low, medium and high temperature storages according to the temperature level of their thermal output. Low temperature TES deliver temperatures below 10°C and are mostly used for cooling and refrigeration applications. Ice storage is by far the most popular low temperature storage with a reported 1 GW installed in the United States [IEA, 2014]. Cold water storage is another popular application with a high installed capacity, while other systems such as aquifer TES and borehole TES have also been commercialized. Ongoing research is focusing on discovering new Phase Changing Materials (PCM) for the development of latent heat storages on temperature levels above and below 0°C.

Medium temperature TES cover the range between 10°C and 250°C. Use of hot water tanks as a buffer storage for domestic hot water supply is probably the most widespread TES application in this category with temperatures reaching up to 80-90°C. Medium temperature TES can be also used in the industrial sector for the storage of process heat as well as in centralised systems for district heating (e.g. combined heat and power plants).

High temperature TES starts at temperatures above 250°C. Probably the most widespread application is in concentrated solar power (CSP) plants. In these applications TES is employed to compensate for the inherent intermittent nature of solar energy. The storage is charged in times of high solar irradiation and discharged in conditions of low solar irradiance, thus increasing the dispatchability and operation time of the solar power plant. A list of important TES applications with their corresponding storage temperature range can be found in Figure 4.4.

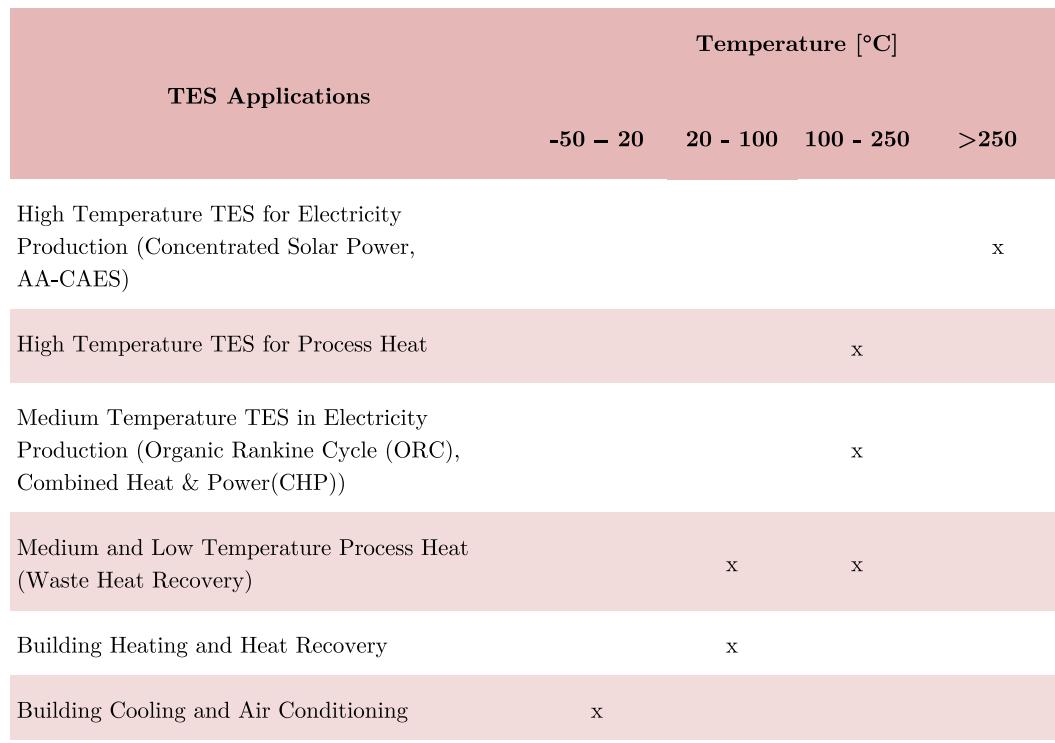


Figure 4.4: Important TES Applications with corresponding storage temperature range.

4.4 Thermodynamic and Heat Transfer Aspects

4.4.1 Energy and Exergy balances in TES (1st and 2nd Law of Thermodynamics)

Energy balance of TES (1st Law of Thermodynamics)

The power balance of an open system describes the basis for the load capacity of a thermal storage:

$$\frac{dE}{dt} = \sum \dot{Q} + \sum P + \sum_{in} \dot{m}_{in} \left(h + \frac{c^2}{2} + g z \right)_{in} - \sum_{out} \dot{m}_{out} \left(h + \frac{c^2}{2} + g z \right)_{out} \quad (4.1)$$

Where dE/dt is the storage term of the power balance equation.

For thermal storage systems the velocity c and the height z are not important can be neglected. Therefore, we have:

$$\frac{dE}{dt} = \sum \dot{Q} + \sum P + \sum_{in} \dot{m}_{in} h_{in} - \sum_{out} \dot{m}_{out} h_{out} \quad (4.2)$$

Exergy balance of TES (2nd Law of Thermodynamics)

The 2nd law of thermodynamics can be written as an exergy balance. It describes the balance of fully usable energy and the exergy loss, i.e. the loss of energy quality. Therefore, it is a true measure of the difference to a fully reversible storage process. Every form of energy consist of exergy and anergy, where one of the two parts can be equal to zero:

$$Energy = Exergy + Anergy \quad (4.3)$$

The 1st law of thermodynamics can be formulated as:

In closed systems the sum of exergy and anergy remains constant.

Exergy and anergy are defined as follows:

- **Exergy:** Energy with unlimited changeability
(mechanical, electrical, potential, kinetic energy are pure exergy)
- **Anergy:** Energy with no changeability
(thermal energy at environmental conditions is pure anergy)
- **Exergy + Anergy:** Energy with limited changeability
(thermal energy consists of exergy and anergy)

The 2nd law of thermodynamics can be formulated based on exergy and anergy as follows:

1. In all irreversible processes a part of the exergy is converted into anergy.
2. The amount of exergy remains constant only in reversible processes.
3. It is impossible to convert anergy into exergy.

This results in the exergy balance:

$$\frac{d\Xi}{dt} = \sum P + \sum \dot{\Xi}_Q + \sum_{in} \dot{\Xi}_{H,in} - \sum_{out} \dot{\Xi}_{H,out} - \sum \dot{\Xi}_{irr} \quad (4.4)$$

with the value of the exergy loss $\dot{\Xi}_{irr} = T_{Amb} \dot{S}_{irr}$ being zero for reversible storage processes and positive under real conditions (irreversible processes). The terms in the balance are given below.

Exergy of heat:

$$-d\Xi_Q = \left(1 - \frac{T_{Amb}}{T}\right) dQ. \quad (4.5)$$

Exergy of a flowing fluid:

$$\dot{\Xi}_H = \dot{m} \left[(h - h_{Amb}) + \frac{1}{2} c^2 + gz + T_{Amb}(s_{Amb} - s) \right] \quad (4.6)$$

Anergy of a flowing fluid:

$$\dot{\Lambda}_H = \dot{m} \left[h_{Amb} + T_{Amb}(s - s_{Amb}) \right] \quad (4.7)$$

For an ideal gas:

$$\dot{\Xi}_H = \dot{m} \left[c_p(T - T_{Amb}) - T_{Amb} \left(c_p \ln \frac{T}{T_{Amb}} - R_i \ln \frac{p}{p_{Amb}} \right) \right] \quad (4.8)$$

For fluids (incompressible):

$$\dot{\Xi}_H = \dot{m} \left[c_p \left(T - T_{Amb} - T_{Amb} \ln \frac{T}{T_{Amb}} \right) + v(p - p_{Amb}) \right] \quad (4.9)$$

Example 1: Electrically-heated water storage

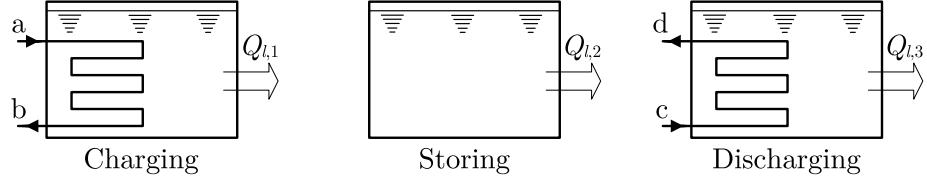
Example 2: Charging and discharging an indirect thermal storage


Figure 4.5: The three stages in a simple TES process, including thermal losses to the environment [Dincer and Rosen, 2002].

Energy balance

$$\Delta E = \Delta m_C(h_a - h_b) + \Delta m_D(h_c - h_d) - \sum_{i=1}^3 Q_{l,i} \quad (4.10)$$

$\Delta m_C(h_a - h_b)$ and $\Delta m_D(h_c - h_d)$ represent the total amount of energy that was transferred in and out of the storage system with the heat transfer fluid during the entire charging and discharging period respectively

Exergy balance

$$\Delta \Xi = \Delta m_C (\zeta_a - \zeta_b) - \Delta m_D (\zeta_d - \zeta_c) - \Xi_{Q_l} - \Xi_{irr} \quad (4.11)$$

where $\zeta_a, \zeta_b, \zeta_c$ and ζ_d are the specific exergies at states a, b, c and d . Ξ_{Q_l} represents the exergy loss associated with the heat loss. Ξ_{irr} is the exergy loss which is proportional to entropy creation and is known as the Gouy-Stodola relation. The terms are given respectively by:

$$\zeta_a - \zeta_b = (h_a - h_b) - T_{Amb}(s_a - s_b) \quad (4.12)$$

$$\zeta_d - \zeta_c = (h_d - h_c) - T_{Amb}(s_d - s_c) \quad (4.13)$$

$$\Xi_{irr} = \sum_{j=1}^3 (\Xi_{irr})_j = \sum_{j=1}^3 T_{Amb}(S_{irr})_j \quad (4.14)$$

$$\Xi_{Q_l} = \sum_{j=1}^3 (\Xi_{Q_l})_j = \sum_{j=1}^3 \left(1 - \frac{T_{Amb}}{T_j}\right) (Q_l)_j \quad (4.15)$$

4.4.2 Energetic and Exergetic Analyses of TES

While many thermal energy storages are in operation, no generally valid basis for comparing different storages under different conditions has found acceptance. Energetic analysis are conventionally used to measure the performance of energy storages. They are based on the 1st law of thermodynamics, as they account for the ratio of the energy recovered from the storage to the energy inputs. While energy can not be destroyed or created in a closed system (storage and its environment), it can get degraded in its quality, eventually reaching the state in which it is in complete equilibrium with the ambient, hence no further energy can be extracted. Therefore a purely energetic analysis is inadequate because it does not take into account all necessary considerations (e.g. temperatures of the supplied and the recovered thermal energy, the surroundings and the storage duration).

Energy η and exergy ψ efficiencies can be defined as [Dincer and Rosen, 2002]:

$$\eta = \frac{\text{Energy in outputs}}{\text{Energy in inputs}} = 1 - \frac{\text{Energy loss}}{\text{Energy in inputs}} \quad (4.16)$$

$$\psi = \frac{\text{Exergy in outputs}}{\text{Exergy in inputs}} = 1 - \frac{\text{Exergy loss}}{\text{Exergy in inputs}} \quad (4.17)$$

Exergy loss describes both, the exergy loss due to energy loss and due to entropy increase. Alternatively, with equations 4.18 - 4.21 it can be written in following form:

$$\eta = \frac{\text{Energy recovered from TES during discharging}}{\text{Energy input to TES during charging}} \quad (4.18)$$

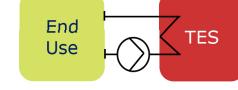
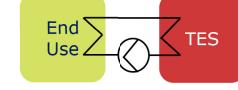
$$= \frac{\Delta m_D(h_a - h_c)}{\Delta m_C(h_a - h_b)} = 1 - \frac{Q_l}{\Delta m_C(h_a - h_b)}$$

$$\psi = \frac{\text{Exergy recovered from TES during discharging}}{\text{Exergy input to TES during charging}} \quad (4.19)$$

$$= \frac{\Delta m_D(\zeta_d - \zeta_c)}{\Delta m_C(\zeta_a - \zeta_b)} = 1 - \frac{\Xi_{Q_l} + \Xi_{irr}}{\Delta m_C(\zeta_a - \zeta_b)}$$

4.4.3 Heat exchanger concepts in TES

Different heat exchanger concepts are applied in thermal storage applications. A main distinction between concepts is given by the Heat Storage Medium (HSM), the Heat Transfer Medium (HTM) and the End Use Medium (EUM). Depending on the setup, the media are directly transferred or additional heat exchangers are used. The distinction is graphically displayed in Figure 4.7.

	Direct Supply HTM=EUM	Indirect Supply HTM≠EUM
Direct Storage HSM=HTM	 <ul style="list-style-type: none"> • District heating TES • Domestic hot water tank 	 <ul style="list-style-type: none"> • Ice storage with water withdrawal
Indirect Storage HSM ≠ HTM	 <ul style="list-style-type: none"> • Direct evaporation of HTF for Rankine Cycle 	 <ul style="list-style-type: none"> • Ice storage with brine • Airlight TES

HSM: Heat Storage Medium, **HTM:** Heat Transfer Medium, **EUM:** End Use Medium

Figure 4.6: Heat exchange options between the Heat Storage Medium (HSM), Heat Transfer Medium (HTM) and End Use Medium (EUM).

4.4.4 Heat transfer and losses

Tube heat exchangers and plate heat exchangers are the most commonly used heat exchanger concepts for thermal energy storage systems. The calculation of the available heating and cooling power is one of the most important aspects in the storage design process.

The discharging and charging power of the thermal energy storage system can be calculated based on classical heat transfer theory. We mainly refer to the script of Thermodynamics and Heat transfer as given in the appendix. The most relevant heat transfer design equations are those related to heat transfer through flat walls (plates) and tubes of any kind.

a) Heat transfer through a flat wall

We consider two fluid streams with a temperature T_1 and T_2 , separated by a wall with thickness l (Figure 4.8).

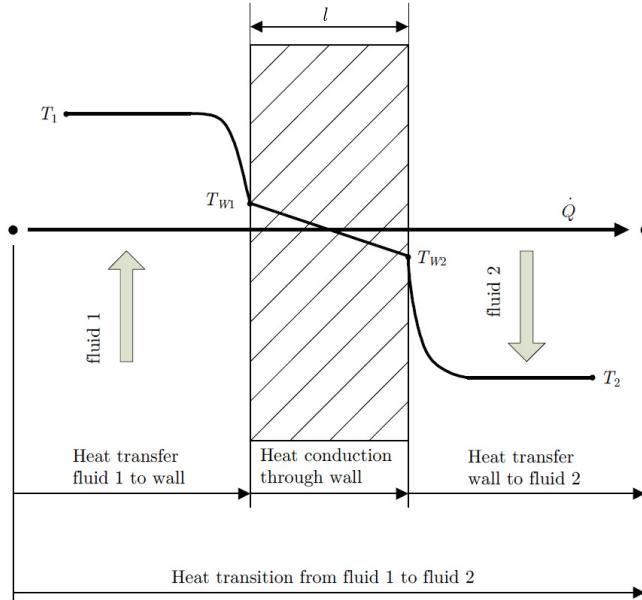


Figure 4.7: The three stages of heat transition through a flat wall

Three distinct heat transfer processes are important for this problem:

- Heat transfer fluid 1 \rightarrow Wall: $\dot{Q}_1 = \alpha_1 A(T_1 - T_{W1})$
- Heat conduction through the wall: $\dot{Q}_\lambda = \frac{\lambda}{l} A(T_{W1} - T_{W2})$
- Heat transfer Wall \rightarrow fluid 2: $\dot{Q}_2 = \alpha_2 A(T_{W2} - T_2)$

Here α denotes the convective heat transfer coefficient. The overall heat transfer can be summarized as

$$\dot{Q} = kA(T_1 - T_2), \quad (4.20)$$

where k [W/m²K] is the overall heat transfer coefficient. Assuming steady state conditions the heat flows for all the processes are equal: $\dot{Q}_1 = \dot{Q}_\lambda = \dot{Q}_2 = \dot{Q}$.

Therefore:

$$\frac{1}{k} = \frac{1}{\alpha_1} + \frac{l}{\lambda} + \frac{1}{\alpha_2}. \quad (4.21)$$

This can be generalized for a wall with n -layers :

$$\frac{1}{k} = \frac{1}{\alpha_1} + \sum_1^n \frac{l_i}{\lambda_i} + \frac{1}{\alpha_2}. \quad (4.22)$$

b) Heat transfer through a tube wall

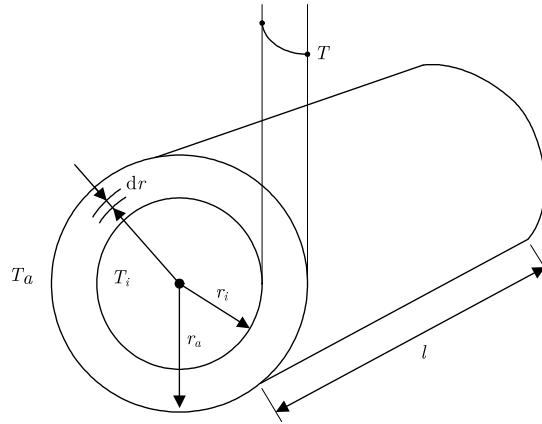


Figure 4.8: The heat transition trough a tube wall

Figure 4.9 shows the temperature profile in the case of heat transfer trough a tube wall. We consider the heat transfer from a hot fluid flowing in the tube to cold surroundings, which entails three heat transfer processes:

- Heat transfer fluid i \rightarrow Inner tube wall: $\dot{Q}_i = \alpha_i 2\pi r_i l (T_i - T_{Wi})$
- Heat conduction through the tube wall: $\dot{Q} = \frac{\lambda 2\pi l}{\ln \frac{r_o}{r_i}} (T_{Wi} - T_{Wo})$
- Heat transfer outer tube wall \rightarrow Fluid a: $\dot{Q}_o = \alpha_o 2\pi r_o l (T_{Wo} - T_o)$

In analogy to the flat wall case, the heat flow \dot{Q} can be expressed as:

$$\dot{Q} = k_r 2\pi r l (T_i - T_o), \quad (4.23)$$

where

$$\frac{1}{k_r r} = \frac{1}{\alpha_i r_i} + \frac{1}{\lambda} \ln \frac{r_o}{r_i} + \frac{1}{\alpha_o r_o}. \quad (4.24)$$

The radius r is only introduced for consistency and only the product $k_r r$ is needed in the calculation.

If the tube wall is made up of several layers n , then:

$$\frac{1}{k_r r} = \frac{1}{\alpha_i r_i} + \frac{1}{\lambda_1} \ln \frac{r_1}{r_i} + \frac{1}{\lambda_2} \ln \frac{r_2}{r_1} + \dots + \frac{1}{\lambda_n} \ln \frac{r_o}{r_n} + \frac{1}{\alpha_o r_o} \quad (4.25)$$

Exergy losses in heat transfer processes

To transfer a heat flow rate $d\dot{Q}$ through a wall with the surface area A , a temperature difference ΔT is required. Due to the temperature difference an irreversible exergy loss flow rate $\dot{\Xi}_{irr}$ occurs. The loss depends on the temperature T , the temperature difference ΔT and the ambient temperature T_{Amb} :

$$d\dot{\Xi}_{irr} = -T_{Amb} \left(\dot{S}_1 - \dot{S}_2 \right) = -T_{Amb} \left(\frac{\dot{Q}}{T_1} - \frac{\dot{Q}}{T_2} \right) \quad (4.26)$$

$$\dot{\Xi}_{irr} = \dot{Q} T_{Amb} \frac{\Delta T}{T(T + \Delta T)} \quad (4.27)$$

or as an approximation:

$$\dot{\Xi}_{irr} \approx \dot{Q} T_{Amb} \frac{\Delta T}{T^2} \quad (4.28)$$

This equation shows, that the exergy loss flow rate due to heat transfer is proportional to the temperature difference ΔT and approximatively inversely proportional to the square of T (if ΔT is small compared to T). In other words: A certain ΔT at a high temperature (e.g. combustion process) is significantly less harmful than at a lower temperature (e.g. refrigeration plant).

4.4.5 Heat exchanger design

In a heat exchanger the overall energy balance is independent of the structure of the heat exchanger and the design of the fluid channels. Figure 4.11 shows a schematic of a heat exchanger and the typically used symbols. The temperatures of the fluids are labelled as ϑ_1 and ϑ_2 , where $\vartheta_1 > \vartheta_2$. The indices α and ω indicate the inlet and the outlet of the heat exchanger, respectively.

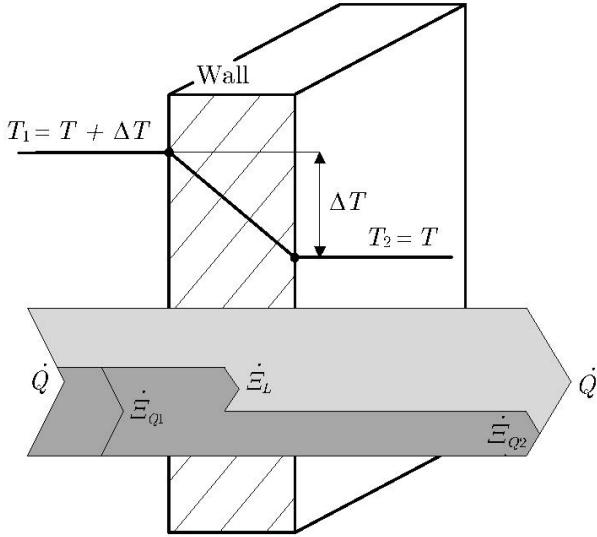


Figure 4.9: The loss of exergy due to a temperature gradient

If the heat exchanger is well insulated and the kinetic and potential energies are neglected, the 1st law of thermodynamics applied to the control volume SB1 results in the following balance equation:

$$\dot{m}_1 h_{1\alpha} = \dot{m}_1 h_{1\omega} + \dot{Q} \quad \rightarrow \quad \dot{Q} = \dot{m}_1 (h_{1\alpha} - h_{1\omega}) \quad (4.29)$$

Here \dot{m} is the mass flow of the fluids and $h_{1\alpha}$, $h_{1\omega}$, $h_{2\alpha}$ and $h_{2\omega}$ are the specific enthalpies of the fluids at the inlet and the outlet of the heat exchanger.

For a constant specific heat capacity c_{p1} we get:

$$\dot{Q} = \dot{m}_1 c_{p1} (\vartheta_{1\alpha} - \vartheta_{1\omega}) = CP_1 (\vartheta_{1\alpha} - \vartheta_{1\omega}), \quad (4.30)$$

where CP_1 indicates the heat capacity flow rate ($CP_1 = \dot{m}_1 c_{p1}$).

For the control volume SB 2 the energy balance is:

$$\dot{m}_1 h_{1\alpha} + \dot{m}_2 h_{2\alpha} = \dot{m}_1 h_{1\omega} + \dot{m}_2 h_{2\omega} \quad (4.31a)$$

For constant specific heat capacities equation 4.37a can be written as:

$$\dot{m}_1 c_{p1} (\vartheta_{1\alpha} - \vartheta_{1\omega}) = \dot{m}_2 c_{p2} (\vartheta_{2\alpha} - \vartheta_{2\omega}) \quad (4.31b)$$

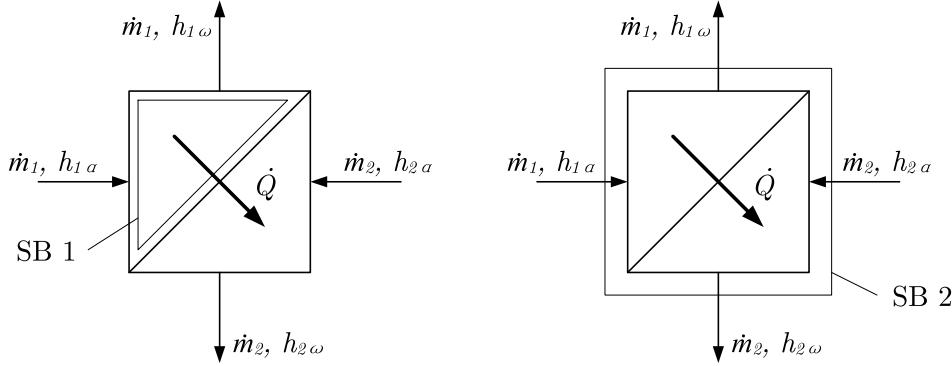


Figure 4.10: Schematic illustration of the energy balance of a heat exchanger

$$CP_1(\vartheta_{1\alpha} - \vartheta_{1\omega}) = CP_2(\vartheta_{2\alpha} - \vartheta_{2\omega}) \quad (4.31c)$$

Average Temperature Difference

In general the temperatures of the fluid changes while flowing through a heat exchanger. An important exception is the case of a pure fluid changing its phase. In this case the fluid temperature remains constant. In a parallel flow configuration, both fluids tend to the same outlet temperature, whereas in a counter flow configuration the outlet temperature of the cooler fluid can be higher than that of the warmer one.

In the design process, the logarithmic mean temperature is used to estimate the heat flow rate. The logarithmic mean temperature difference is always smaller than the arithmetic mean difference and is defined by equation 4.38.

$$\Delta T_m = \frac{\Delta T_a - \Delta T_b}{\ln \frac{\Delta T_a}{\Delta T_b}}; \quad \text{Heat flux: } \dot{Q} = kA\Delta T_m \quad (4.32)$$

4.5 The NTU Method

(Number of Transfer Units - Effectiveness)

As discussed in the previous chapter, in counter flow and parallel flow heat exchanger configurations the overall heat transfer coefficient k and the area A are often used. However, in practical applications these values are often

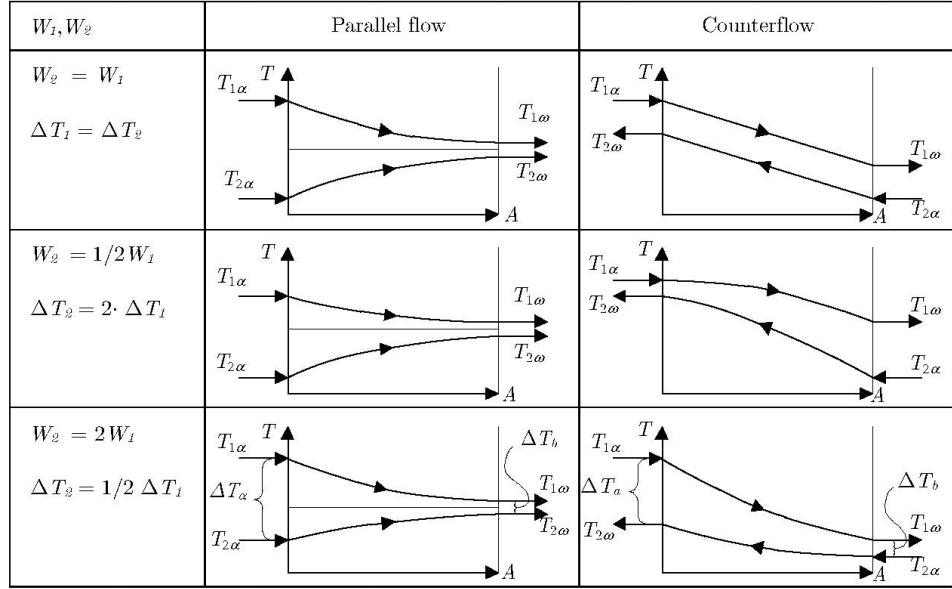
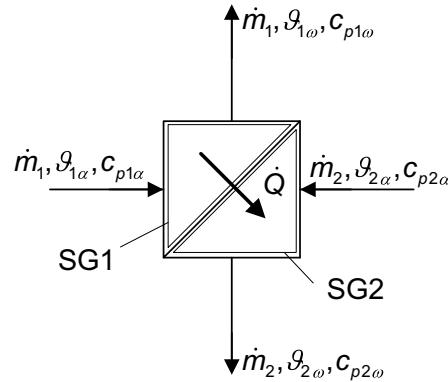


Figure 4.11: Inlet and outlet temperature of the parallel flow and the counterflow heat exchanger

not available which motivates the *NTU*-Method. This method allows to determine the operational characteristic of a heat exchanger and therefore to define its layout without great effort.

4.5.1 Energy Balance of a Heat Exchanger



Applying the first law of thermodynamics to the control volume SG1 and assuming that the difference of the kinetic and potential energy is equal

to zero (Inlet = Outlet), the following energy balance can be written for a system without losses:

$$\dot{m}_1 c_{p1\alpha} \vartheta_{1\alpha} = \dot{m}_1 c_{p1\omega} \vartheta_{1\omega} + \dot{Q}$$

For a constant specific heat capacity ($c_{p1\alpha} = c_{p1\omega} = c_p$), the following equation can be derived:

$$\dot{Q} = \dot{m}_1 c_p (\vartheta_{1\alpha} - \vartheta_{1\omega}) = CP_1 (\vartheta_{1\alpha} - \vartheta_{1\omega})$$

Similarly the energy balance for the control volume SG1 can be written as:

$$\dot{Q} = \dot{m}_2 c_{p2} (\vartheta_{2\omega} - \vartheta_{2\alpha}) = CP_2 (\vartheta_{2\omega} - \vartheta_{2\alpha})$$

The combination of the two equations results in:

$$\frac{CP_1}{CP_2} = \frac{\vartheta_{2\omega} - \vartheta_{2\alpha}}{\vartheta_{1\alpha} - \vartheta_{1\omega}} = \frac{\Delta\vartheta_2}{\Delta\vartheta_1}$$

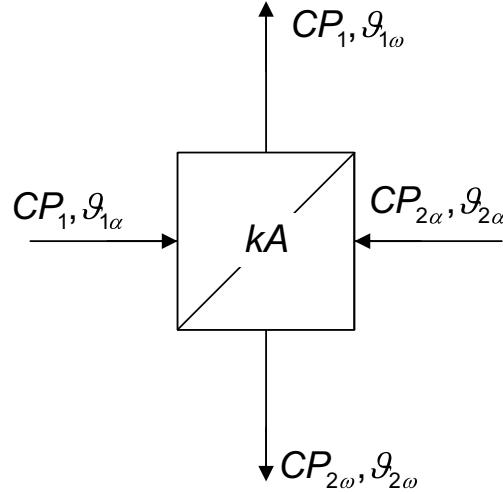
The change of temperature of both fluid flows is described by combining the first law of thermodynamics for both systems. The ratio of the heat capacity fluxes is the inverse of the ratio of temperature changes in the two systems.

4.5.2 Layout of a Heat Exchanger Using the NTU-Method

In the following section the *NTU*-method used to design a heat exchanger is discussed in detail. A clear advantage of this method is that the procedure is independent of the heat exchanger configuration and can always be applied in the same manner. Therefore, the *NTU*-method can be seen as a standard formula for the layout of heat exchangers.

4.5.3 Dimensionless Quantities

The design of a heat exchanger requires the consideration of the relevant quantities of influence. The number of these quantities can be reduced by introducing dimensionless quantitis. The following diagram illustrates the previously discussed quantities.



The effectiveness of the heat exchanger is defined by the transfer capacity kA . The two mass flows are characterized by their heat capacity fluxes CP_1 and CP_2 , the inlet temperatures $\vartheta_{1\alpha}$ and $\vartheta_{2\alpha}$, as well as their outlet temperatures $\vartheta_{1\omega}$ and $\vartheta_{2\omega}$. The quantities of influence are now reduced by the use of the following three dimensionless quantities:

1. Dimensionless change in temperature:

$$P_1 = \frac{\vartheta_{1\alpha} - \vartheta_{1\omega}}{\vartheta_{1\alpha} - \vartheta_{2\alpha}} \text{ und } P_2 = \frac{\vartheta_{2\omega} - \vartheta_{2\alpha}}{\vartheta_{1\alpha} - \vartheta_{2\alpha}}$$

The denominator contains the maximum temperature difference within the system. Therefore P_i is always < 1 and can be seen as a measure for the potential which is available. The dimensionless change of temperature is also known as **recovered heat** or **cooling coefficient**.

2. Dimensionless transfer capacity or Number of Transfer Units:

$$NTU_1 = \frac{kA}{CP_1} \text{ und } NTU_2 = \frac{kA}{CP_2}$$

3. Heat capacity flux Ratio:

$$R_1 = \frac{CP_1}{CP_2} \text{ und } R_2 = \frac{CP_2}{CP_1}$$

The three characteristic dimensionless number NTU , P and R are combined in the **heat exchanger operational characteristic**. If two of the three numbers are given, the characteristic in the form of a diagram or an equation allows to determine the missing number.

4.5.4 Operational Characteristics

The operational characteristics of different heat exchangers can be determined by analyzing the temperature profiles of both fluid flows. Typically the characteristics are dependent on the layout of the heat exchanger as well as the guidance of the fluid through the heat exchanger.

A simple form of a heat exchanger is the double pipe heat exchanger. Two pipes of different diameter are arranged in a concentrical configuration. As a result, one fluid flows in the smaller pipe and the other in the annulus formed by the two pipes. In this layout the heat exchanger can operate in both, a parallel and a counterflow configuration.

Double Pipe Heat Exchanger with Constant Wall Temperature

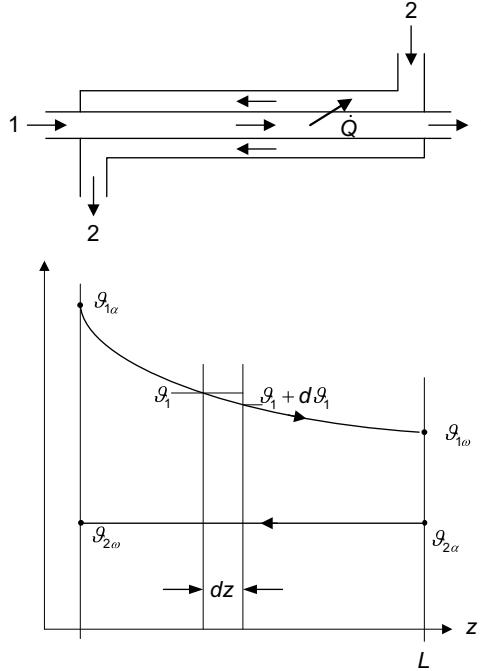
To obtain the operational characteristic of the double pipe heat exchanger, the mathematical relations between the individual quantities have to be derived:

$$P_i = f(NTU_i, R_i) \text{ or } NTU_i = f(P_i, R_i)$$

As an example we will consider the simplest case. The assumption is made, that the temperature of the cooler fluid remains constant when passing through the heat exchanger. This case can occur when the colder fluid evaporates isobarically due to heat absorption and therefore cannot overheat. In literature this assumption is often designated as constant wall temperature. The temperature profile in direction of the flow can be illustrated as follows:

The assumption of constant wall temperature requires the following conditions:

- In every cross section $\vartheta_1 > \vartheta_2$ has to be valid, if ϑ_2 is the temperature of the colder fluid.
- The temperature ϑ_1 depends only on the streamwise coordinate z of the fluid 1



- $P_2 = 0$ has to be valid for the dimensionless change of temperature for the colder fluid
- The heat capacity flux of the colder fluid has to converge towards an infinitely high value (isobaric evaporation)
- This results in: $R_1 = 0$ and $R_2 = \infty$

This allows to identify the operational characteristic with minimal effort, as only NTU_1 and P_1 have to be defined.

The derivation of the characteristic is now discussed:

A heat flux $d\dot{Q}$ passing through the surface dA can be described as follows:

$$d\dot{Q} = k(\vartheta_1 - \vartheta_2)dA = kA(\vartheta_1 - \vartheta_2)\frac{dz}{L}$$

Based on the first law of thermodynamics, the following equation applies for the heat flux:

$$d\dot{Q} = \dot{m}_1 c_{p1} (\vartheta_1 - (\vartheta_1 + d\vartheta_1)) = -CP_1(d\vartheta_1)$$

Combining the previous two equations, the change of the temperature of the warmer fluid can be described as

$$d\vartheta_1 = -\frac{kA}{CP_1}(\vartheta_1 - \vartheta_2)\frac{dz}{L} = -NTU_1(\vartheta_1 - \vartheta_2)\frac{dz}{L}$$

Dividing this equation by $\vartheta_1 - \vartheta_2$ results in

$$\frac{d(\vartheta_1)}{\vartheta_1 - \vartheta_2} = -NTU_1\frac{dz}{L}$$

The integration from $z = 0$ to $z = L$ under the assumption of $\vartheta_2 = const$ and $\vartheta_1 = f(z)$ yields:

$$\int_{\vartheta_{1\alpha}}^{\vartheta_{1\omega}} \frac{d(\vartheta_1)}{\vartheta_1 - \vartheta_2} = \int_{z=0}^{z=L} -NTU_1\frac{dz}{L}$$

As a result, the following equations can be formed:

$$\ln \frac{\vartheta_{1\omega} - \vartheta_2}{\vartheta_{1\alpha} - \vartheta_2} = -NTU_1 \underbrace{\frac{L - 0}{L}}_1$$

$$\vartheta_{1\omega} - \vartheta_2 = \vartheta_{1\alpha} - \vartheta_2 - (\vartheta_{1\alpha} - \vartheta_{1\omega})$$

Rewriting the temperature differences the equation for the operational characteristic can be determined:

$$-\ln(1 - P_1) = NTU_1$$

Which can also be expressed in terms of the dimensionless quantity P :

$$P_1 = 1 - e^{-NTU_1}$$

As a result, we have a simple equation for the operational characteristic of a double pipe heat exchanger in a simplified setup. The relation between NTU and P can be illustrated as follows:

NTU	P	Meaning
1	0.64	64% of possible transfer power
3	0.95	95% of possible transfer power
5	0.99	99% of possible transfer power

Therefore, a heat exchanger with $NTU = 5$ almost fully cools down according to the illustrated example. However, this does not imply the most economic solution as the surface area has to be quite high for this example to work, as $NTU = \frac{kA}{CP_1}$.

Consequently, it is not meaningful to configure a heat exchanger with an NTU value greater than 5.

Following the same procedure, the equations for the operational characteristic can be defined for any double pipe heat exchangers in parallel and counter flow configuration (i.e. if temperatures are not constant along the heat exchanger or $R \neq 0$). A detailed derivation of these equations can be found in literature (VDI Heat Atlas).

The equations for a double pipe heat exchanger in counter flow configuration is defined as follows:

$$P_i = \frac{1 - e^{(R_i-1)NTU_i}}{1 - R_i e^{(R_i-1)NTU_i}}$$

rewritten:
$$NTU_i = \frac{1}{1 - R_i} \ln \left(\frac{1 - R_i P_i}{1 - P_i} \right)$$

The operational characteristic is also often illustrated in the form of diagrams, such as the one for a counter flow heat exchanger in Fig. 4.13 :

The coordinate axes are the dimensionless changes of temperature P_1 and P_2 of the fluxes. The heat capacity flux ratios R_1 and R_2 are constant on the diagonal lines, such as illustrated in the figure. NTU_1 and NTU_2 are illustrated as a set of curves. Consequently, if 2 of the 3 dimensionless quantities are given, the third one can easily be determined graphically.

Parallel Flow Double Pipe Heat Exchanger:

Next, the equations for the operational characteristic of the double pipe heat exchanger in a parallel flow configuration are defined. The derivation of the equations is not discussed here and can be found in the previously mentioned literature.

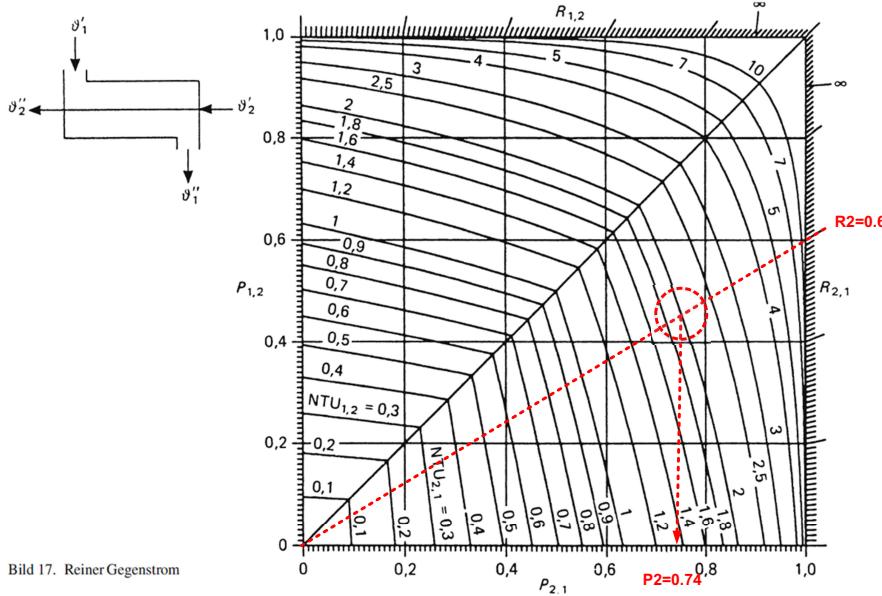


Figure 4.12: NTU diagramm for counter flow heat exchanger

$$P_i = \frac{1 - e^{-(1+R_i)NTU_i}}{1 + R_i}$$

$$NTU_i = \frac{-\ln(1 - P_i(1 + R_i))}{1 + R_i}$$

Figure 4.14 illustrates the operational characteristic for the parallel flow configuration:

In a counter flow heat exchanger configuration, the fluids exit the domain at opposite ends. As a result, the outlet temperature $\vartheta_{2\omega}$ can reach higher values than the other outlet temperature $\vartheta_{1\omega}$. A drawback of the parallel flow heat exchanger is that this level of temperature increase can not be accomplished. With this in mind, a predefined change of temperature for a parallel flow heat exchanger can only be achieved if the argument of the logarithm in the corresponding equation is positive.

Therefore, the following statement has to be valid:

$$(1 - P_i(1 + R_i)) > 0$$

This is only valid if the following requirement is given:

$$P_i < \frac{1}{1+R}$$

The previously introduced dimensionless quantities allow to perform a layout for a heat exchanger without great effort. Two significant types of layout procedures can be defined:

Case A: Power of a Given Heat Exchanger

The exchange capacity kA is given for a specific heat exchanger. Furthermore, the inlet temperature or at least the temperature difference between the two inlet temperatures ($\vartheta_{1\alpha} - \vartheta_{2\alpha}$) and the heat capacity fluxes CP_1 and CP_2 are given. The given quantities allow to determine NTU_1 and R_1 . If the operational characteristic is known, P_1 can also be calculated which allows to identify the power of the heat exchanger. The procedure can be summarized as follows (The requested quantities are circled with dashed lines):

Requested quantities: $\vartheta_{1\omega}, \vartheta_{2\omega}$ and \dot{Q}

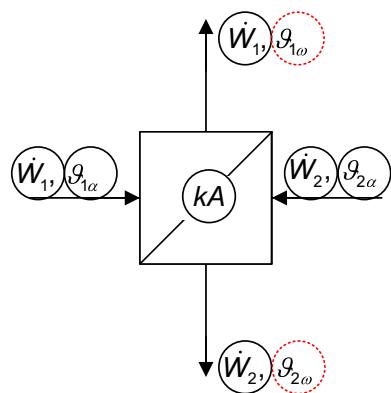
Given quantities: $kA, (\vartheta_{1\alpha} - \vartheta_{2\alpha}), CP_1, CP_2$

Calculate: R_i, NTU_i

Calculate via operational characteristic: P_i

Further calculate from P_i : $\vartheta_{1\omega}, \vartheta_{2\omega}$

Energy balance: \dot{Q}



Case B: Layout for a Specified Power

This case requires the layout of the exchange capacity kA for a specified power of the heat exchanger. The inlet temperatures and the heat capacity fluxes CP_1 and CP_2 are given. The outlet temperatures can be determined via the energy balance equation due to the already specified power. This allows to calculate the dimensionless quantities P_1 and R_1 . NTU_1 can be determined if the operational characteristic is given, which in turn allows to calculate the exchange capacity kA . Consequently, the surface A of the heat exchanger can be determined. This approach can be summarized as follows (Again the requested quantities are circled with dashed lines):

Requested quantities: A

Given quantities: $\dot{Q}, \vartheta_{1\alpha}, \vartheta_{2\alpha}, CP_1, CP_2$

Calculate from the energy balance: $\vartheta_{1\omega}, \vartheta_{2\omega}$

Calculate: R_i, P_i

Calculate via operational characteristic: NTU_1

Further calculate: kA, k, A

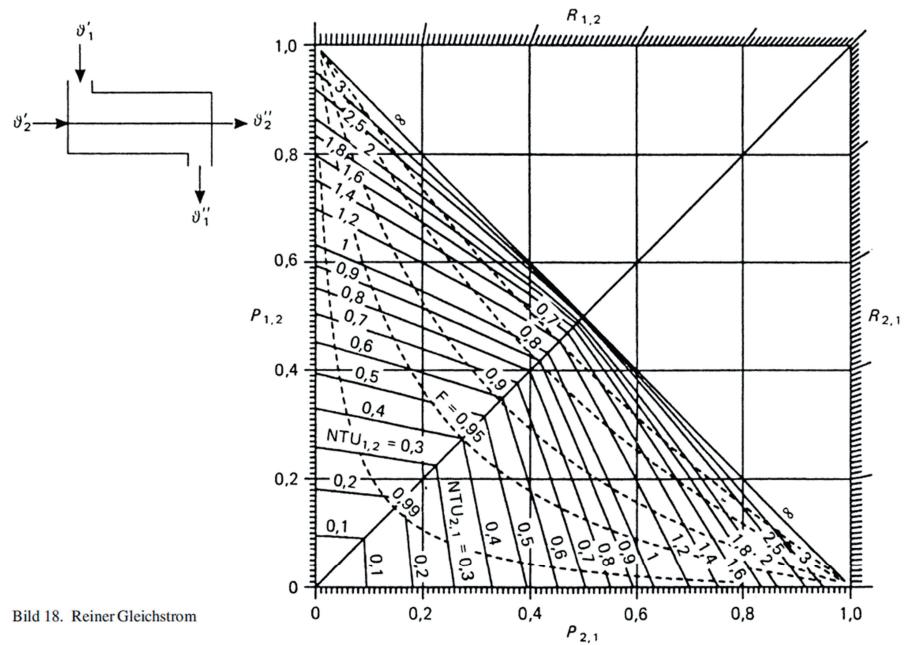


Figure 4.13: NTU diagramm for parallel flow heat exchanger

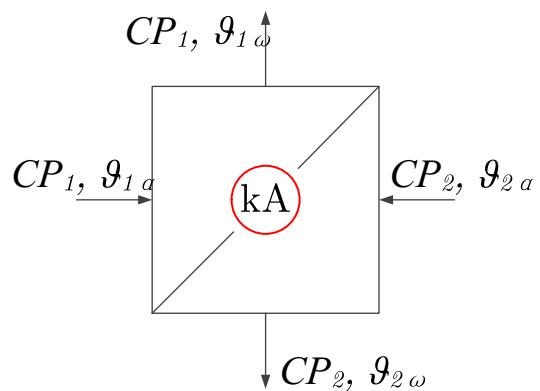


Figure 4.14: The summary of all quantities for case B

4.6 Thermochemical Energy Storage

Thermochemical storage systems use sorption processes or reversible thermochemical processes to store energy with potentially very high energy densities and low heat losses. The processes associated with charging, storing and discharging are schematically represented in Figure 4.16.

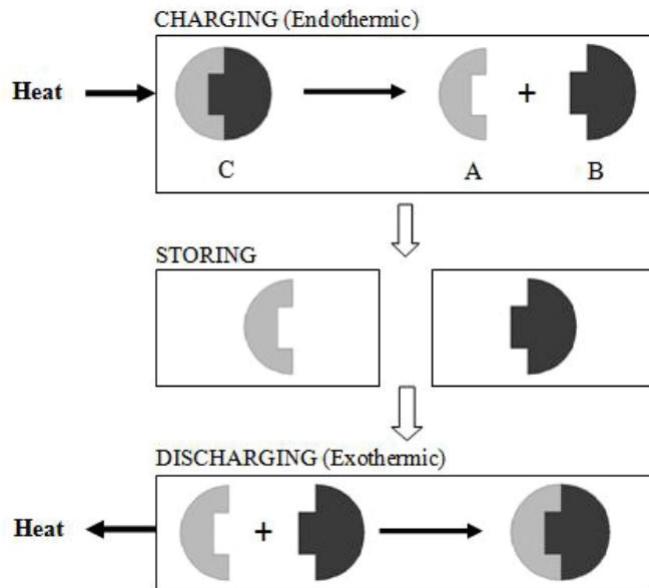
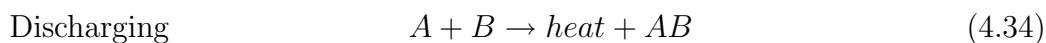


Figure 4.15: Processes taking place during charging, storage and discharging of a thermochemical energy storage systems [Abedin and Rosen, 2011]

During charging AB dissociates into components A and B. This is an endothermic process, meaning it absorbs heat which equals the heat of adsorption in the case of adsorption processes and to the heat of reaction/formation in the case of chemical reactions. The process can be represented as:



Discharging takes place when the components A and B are recombined, with a subsequent heat release which equals the heat of adsorption or heat of reaction. The process can be represented as:



For the storage to be achieved components A and B have to be kept separately after charging and until the energy is needed. As the energy is stored in a chemical form, the storage medium can be stored in ambient temperature leading to minimal heat losses. This property makes thermochemical storage a promising candidate for seasonal storage applications. The overall process after one cycle can be summarized as:

$$\text{Net Process} \quad AB \leftrightarrow A + B \quad (4.35)$$

Sorption

Sorption is a physical or chemical process through which a substance (sorptive) becomes attached to surface or volume of a solid or liquid substance (sorbent). If the sorptive is attached to the surface of the sorbent, the process is called adsorption and if it is attached in its bulk, absorption. In sorption storage systems, charging (equation 4.39) corresponds to the process of desorption, where the sorptive leaves the sorbent with a subsequent energy absorption. During discharging (equation 4.40), the reverse process is taking place, meaning that the sorptive becomes attached to the sorbent, releasing the stored heat.

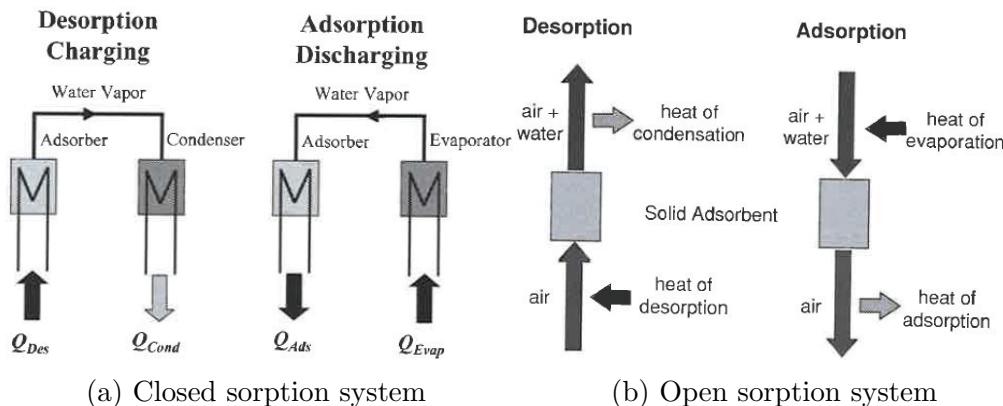


Figure 4.16: Operation principles of a closed and an open sorption system [Paksoy et al., 2007]

Figure 4.17a shows the operation principle of a closed sorption storage system, where both the sorbent and the sorptive (in this case water), have to be stored in the system and kept separately at all times. This leads to a weight increase of the system. In the cases of zeolite or silica gel the stored water accounts for 30-40 % of the weight of the stored material. During charging/desorption, heat Q_{Des} has to be added to the adsorber while the

produced condensation heat Q_{Cond} has to be extracted from the condenser. During adsorption/discharging, heat of adsorption is removed from the adsorber and at the same time heat of evaporation has to be provided to the evaporator. If any of these heats is not delivered or removed, the system will reach thermodynamic equilibrium and the charging/discharging will stop. A commercial application based on a closed system is the self-cooling beer keg (see Figure 4.18). During the storing, a vacuum separates water vapor from zeolite. The evaporator is in contact with the beer. When the valve is opened, the zeolite starts absorbing the vapor, causing the partial pressure to drop and more vapor be produced. The heat of evaporation is removed from the beer, causing it to cool down. The adsorber is located outside the keg, so the heat of adsorption is dissipated to the environment and doesn't affect the cooling of the beer.



Figure 4.17: Key components of the self-cooling bier keg.

Figure 4.17b shows the operation principle of an open system, where air is transporting heat and humidity in and out of the adsorber. Open sorption systems, operate under atmospheric pressure, using the humidity of ambient air as sorptive. Therefore, in contrast to closed systems, there is no need to store the sorptive. During charging/desorption, a dry hot air stream is flowing through the sorbent, where the heat is stored and the water released. The air stream flowing out of the system is cool and wet. During the discharging process a wet, cool air stream flows through the system where water is absorbed and the heat of sorption is released. The air coming out of the system is dry and hot. An example of an open sorption system is the mobile sorption storage for waste heat recovery developed by ZAE Bayern. The

system uses zeolite/water vapour as a working reaction and a truck to transfer the zeolite between the waste heat source and the user (see Figure 4.19). The zeolite weighs 14 t while the whole truck weighs 40 t. The system allows to shift the energy supply and demand in time and space in cases where pipe installation wouldn't be cost effective. A schematic of the working principle of the sorption process can be seen in Figure 4.20.



Figure 4.18: Mobile sorption storage developed by ZAE Bayern (from presentation of A. Hauer in the Energy Storage Conference, 2014).

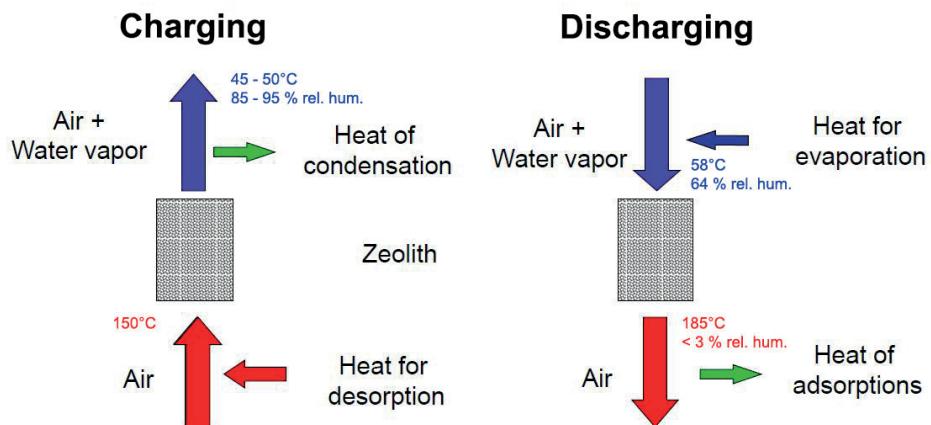


Figure 4.19: Working principle of mobile sorption storage (from presentation of A. Hauer in the Energy Storage Conference, 2014).

Reversible Chemical Reactions

Reversible chemical reactions can also be used to store heat for longer periods at ambient temperatures with very high energy densities. During charging, an endothermic dissociation process takes place (equation 4.39), storing an amount of heat equal to the heat of reaction or enthalpy of formation. The reaction is reversed during discharging when the components are recombined exothermically (equation 4.40), and release the amount of heat stored in the previous step.

Materials

Suitable materials for thermochemical storage applications should have the following criteria:

- Low cost
- Low toxicity, corrosiveness
- High chemical stability
- High heat of formation/sorption
- High heat of formation/sorption
- High reaction/sorption rates
- Suitable reaction/sorption temperatures
- Favorable heat transfer and flow properties for practical applications

Thermochemical Material (C)	Solid Reactant (A)	Working Fluid (B)	Energy Storage Density of Thermochemical Material (GJ/m ³)	Charging Reaction Temperature (°C)
MgSO ₄ ·7H ₂ O	MgSO ₄	7H ₂ O	2.8	122
FeCO ₃	FeO	CO ₂	2.6	180
Ca(OH) ₂	CaO	H ₂ O	1.9	479
Fe(OH) ₂	FeO	H ₂ O	2.2	150
CaCO ₃	CaO	CO ₂	3.3	837
CaSO ₄ ·2H ₂ O	CaSO ₄	2H ₂ O	1.4	89

Figure 4.20: Promising materials for thermochemical energy storage [Abedin and Rosen, 2011]

Materials commonly used as sorbents are zeolites, silicagels, aluminium phosphate, silicoaluminophosphate, metal-organic frameworks (MOFs), activated

carbons and others. Examples of materials investigated for thermochemical energy storage are listed in Figure 4.21.

Applications

Thermochemical storage systems are in an early R&D stage and at the moment quite expensive and far from commercialisation [Hafner, 2014]. Possible application areas for thermochemical storage systems are electricity-free cooling, air-conditioning, adsorption heat-pumps and drying applications. They are often investigated for the storage of solar energy. Despite the unfavorable economics, thermochemical storage is still considered for seasonal storage due to the high energy density, low self-discharge and low thermal losses.

4.7 Sensible Thermal Energy Storage

Sensible thermal energy storage systems use the heat capacity of a gas, a liquid or a solid to store an amount of energy, proportional to the temperature change of the material. In sensible TES the storing material undergoes no phase change, so the amount of energy stored is solely dependent on the mass and heat capacity of the storing material as well as on the temperature change taking place during the storing process. Assuming constant a c_P within the considered temperature range, the stored energy can be given by:

$$\Delta E = m\Delta h = mc_p\Delta T \quad (4.36)$$

where m is the mass of the storage material, h is the specific enthalpy, c_P is the specific heat capacity of the storage material and ΔT is the temperature change taking place during the storing process.

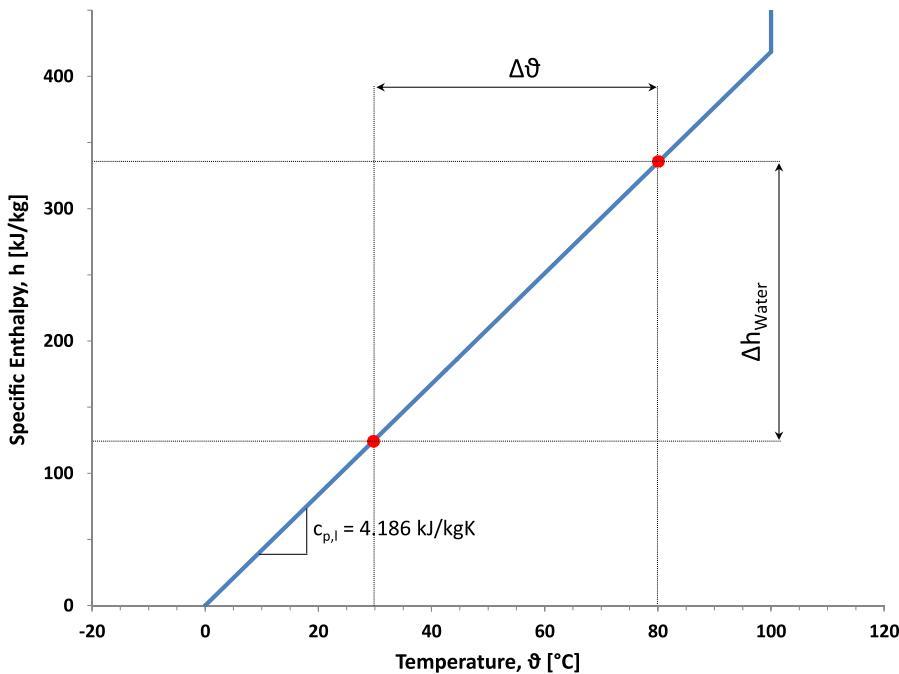


Figure 4.21: Specific enthalpy of water as a function temperature.

Exercise: Design of a Heat Exchanger

Situation

The task is to design a heat exchanger for the heat transfer in a seasonal storage with a volume of 124 m³. The demanded thermal power for the charging as well as for the discharging process is 20 kW. The pipe for the heat exchange is made of ribbed stainless steel. The maximal forerun temperature is 65°C. The maximum storage temperature is to be 60°C. Both fluids, the storage medium and the heat transfer fluid, are water.

Properties of water at 60°C:

- Kinematic viscosity $\nu : 4.75 \cdot 10^{-7} \text{m}^2/\text{s}$
- Prandtl number: 2.983
- Thermal conductivity $\lambda: 0.654 \text{ W/mK}$

Table 4.1: Pipe specifications

	ID [mm]	AD [mm]	s [mm]	Surface [m ² /m]	Darcy Friction Factor [-]	Costs [CHF/m]	λ at 60°C [W/mK]
Steel	30	34	0.3	0.146	0.075	24.-	15
PE	33	40	3.5	-	0.039	7.-	0.33

$$Re = \frac{c \cdot L_{char}}{\nu} \quad (4.37)$$

$$Nu = \frac{\alpha \cdot L_{char}}{\lambda} \quad (4.38)$$

$$\Delta T_m = \frac{\Delta T_a - \Delta T_b}{\ln(\frac{\Delta T_a}{\Delta T_b})} \quad (4.39)$$

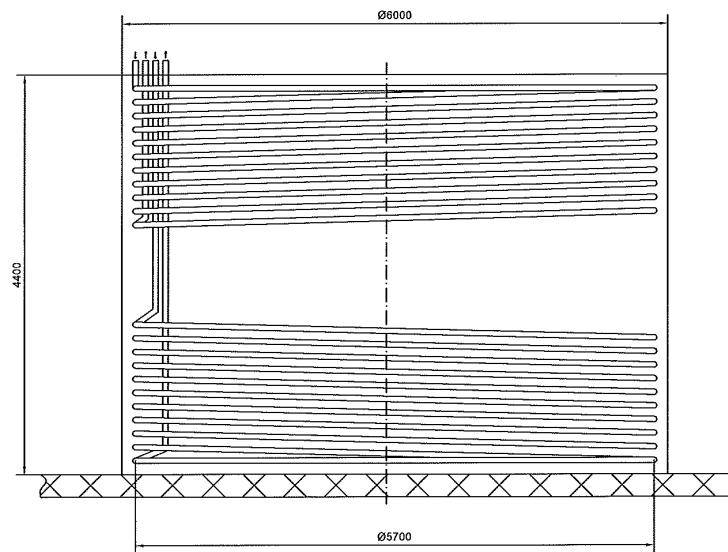


Figure 4.22: Engineering drawing of the seasonal storage

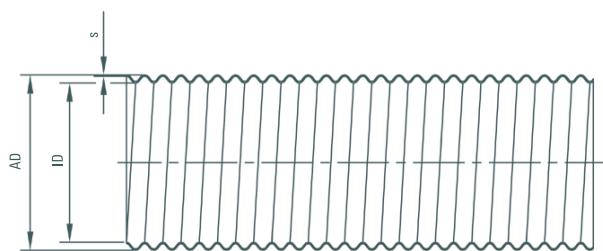


Figure 4.23: Ribbed stainless steel pipe

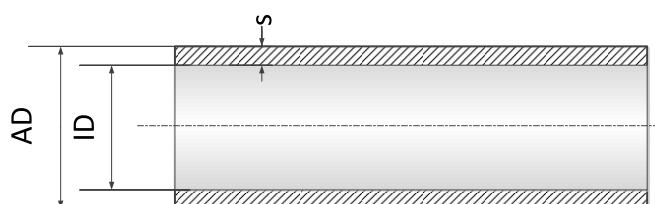


Figure 4.24: Section of the PE plastic pipe

Task

Calculate the required length of the heat exchanger pipe. Additionally it is to be investigated whether the use of a plastic pipe instead of stainless steel was worth it or not.

- (a) Determine the mass flow and the flow rate inside the pipe. The temperature loss between inlet and outlet is assumed to be 4 K.
- (b) A simplified correlation for the Nusselt Number can be used to estimate the heat transfer coefficient:

$$Nu = 0.023Re^{0.8}Pr^{1/3} \quad (4.40)$$

Determine the heat transfer coefficient α_{in} .

Determine the thermal transmittance (assumption: plain wall). The outer heat transfer coefficient is $\alpha_{out} = 400W/m^2K$.

- (c) Determine the mean logarithmic temperature difference within the wall of the pipe.
- (d) Determine the required heat exchange area and the appropriate length for stainless steel and PE pipes.

Sample Solutions

Table 4.2: Solutions

	c [m/s]	k [W/m ² K]	A [m ²]	l [m]	Costs [CHF]
Steel	1.71	377.32	21.2	145.2	3485.-
PE	1.42	75.4	106.1	925.3	6477.-

4.7.1 Sensible storage materials

Storage media for sensible TES should be characterized by:

- High heat capacity
- High thermal conductivity
- Low costs
- Low toxicity/corrosiveness
- High stability
- Simple handling

Some typical sensible storage materials with relevant properties are listed in Table 4.3. Water is one of the most widely applied storage material because of its high heat capacity and very low cost. However its application is mostly limited to the temperature range of 0-100 °C, imposed by its freezing and evaporation temperatures. Metals have a very high heat diffusivity and can be employed when fast charging/discharging is crucial. Non-metallic solids (rocks, concrete etc.) suffer from low thermal conductivity and moderate heat capacity, but can withstand very high temperatures, are cheap and abundant. Packed beds (vessels filled with solid packing material) of non-metallic solids are being investigated mainly for Concentrated Solar Power (CSP) applications. Molten salts are also typically implemented in CSP plants because of their compatibility with high temperatures, their relatively high heat capacity and their ability to act both as a heat transfer fluid and a storage medium. Their main disadvantage is their relatively high price and their high freezing points. As freezing of salt could cause blocking of piping and compromise the system operation, implementation of complementary insulation, monitoring and heating equipment is necessary to ensure the normal operation of the plant.

4.7.2 Sensible TES tank configurations

Three types of tank concepts are typically implemented in TES applications (see Figure 4.26). The simplest and most inexpensive concept is the one-tank, fully-mixed TES which is characterized by one, uniform temperature. It is

Table 4.3: Properties of common sensible storage materials at 20°C [Dincer and Rosen, 2002]

Material	T_{range} [°C]	ρ [kg/m ³]	c_p [J/kgK]	$\rho \cdot c_p$ [MJ/m ³ K]
Sandstone	< 800	2200	712	1.57
Wood	-	700	2390	1.67
Concrete	< 800	2000	880	1.76
Glass	-	2710	837	2.27
Iron	< 800	7900	452	3.57
Gravely earth	< 1200	2050	1840	3.77
Magnetite	< 1500	5177	752	3.89
Water	0-100	988	4182	4.17
Molten salts (Solar salt)	220-600	1899	1495	2.84

typically used in applications which require one output temperature and have conventional heat sources which, in contrast to RE, possess an excessive energy content (e.g. fossil fueled water tanks for domestic hot water). A more complex and sophisticated one-tank TES type is the stratified tank. Such tanks are implemented in systems that are supplied with and/or are required to deliver one or more temperature levels and are typically combined with a low-exergy heat source (e.g. solar, heat pump). As explained in further detail in section 4.7.3, a stratified tank is characterized by a vertical temperature gradient, which connects a high temperature layer (found at the top of the tank) with a low temperature layer (found at the bottom). This allows for a precise temperature output while keeping the tank number at a minimum. For a stratified storage to work properly, an elaborated storage design and operation is required and storage materials which are characterized by a low thermal conductivity are needed. The storage medium can be solid (e.g. packed bed of rocks) or liquid (e.g. water storage). For storage media with high thermal conductivity, where fast equilibration of the hot and cold layers can occur, a two-tank system can become necessary. In such systems, the hot and the cold fluid are kept in separate tanks, increasing the vessel cost but also simplifying the design and operation of the storage unit. A typical application of the two-tank systems is in combination with CSP plants, operating with molten salts. For such applications a two-tank system can have up to 33% higher costs than a stratified storage but can have a significantly higher discharge efficiency [Angelini et al., 2014].

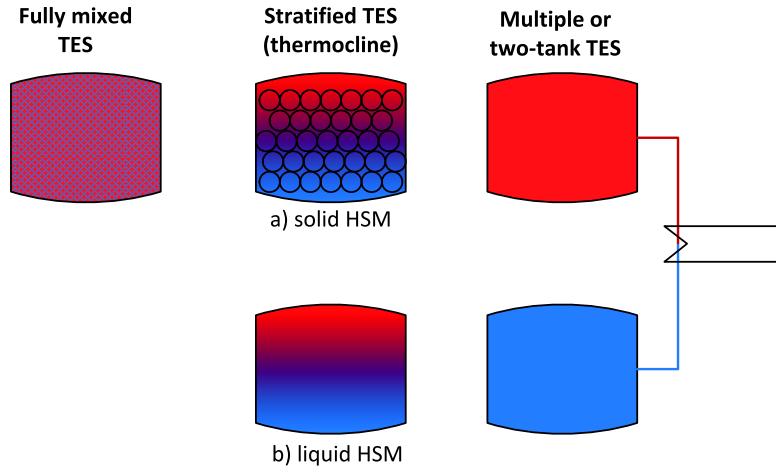


Figure 4.25: Possible sensible TES tank configurations with corresponding temperature distribution.

4.7.3 Stratification

In most sensible heat storage applications, the storage performance depends on its ability to deliver the demanded heat at the right temperature level. Stratification can play a big role in this task. Thermal stratification with a liquid HSM, refers to the temperature distribution of fluid layers (very often water) in a tank characterized by a vertical density gradient. This effect leads the warmer water to rise to the top of the tank and colder water to stay at the bottom, forming a vertical density and temperature gradient in the storage. This temperature gradient formed between the upper and lower layers of constant temperatures is called a thermocline. Three TES cases with different stratification degrees are shown in Figure 4.27. Stratification is very commonly applied in vertical water tanks, with a hot water inlet/outlet at the top and a cold water inlet/outlet at the bottom. Stratified thermal storage can be used for heating as well as for cooling applications. Stratification can be particularly decisive for the energy turnaround of alternative energy systems (e.g. solar collectors, heat pumps) where no excess energy is easily available, in contrast to conventional systems such as fossil-fuel burners and boilers (from presentation of Dr. Michel Haller in SSTES 2014).

There are three main effects that can lead to a loss of the stratification quality [Dincer and Rosen, 2002]:

- Mixing, especially during charging and discharging
- Heat conduction from the hot to the cold layer of the storage and to the tank walls
- Heat losses from the storage to the environment

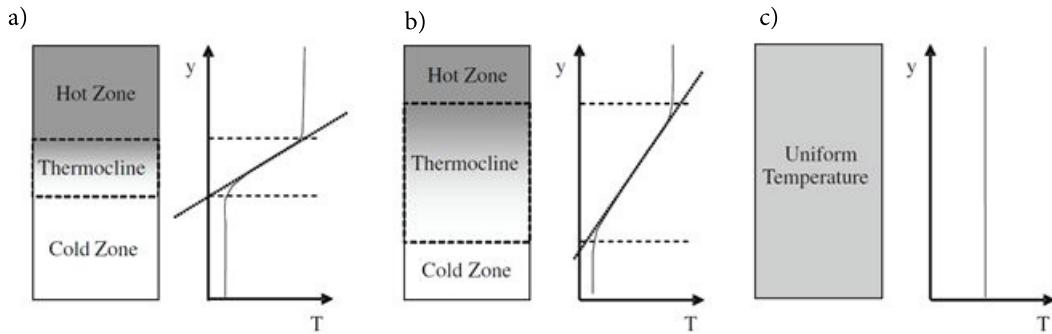


Figure 4.26: a) Highly stratified, b) moderately stratified and c) unstratified TES tanks (from presentation of Dr. Michel Haller in SSTES 2014)

Another factor that could lead to a decrease in the TES performance is the existence of dead water volume in the tank. When assessing the performance of a stratified TES an exergy rather than an energy analysis should be used. More details on this topic are given in the following section.

Exergy Analysis of Thermally Stratified Storages

The energy E and exergy Ξ in a TES can be calculated by integrating over the entire storage mass m :

$$E = \int_m e \, dm \quad (4.41)$$

$$\Xi = \int_m \zeta \, dm \quad (4.42)$$

where e stands for the specific energy and ζ for the specific exergy. For an ideal liquid, e and ζ are functions only of temperature T . They can be expressed by:

$$e(T) = c_p(T - T_{Amb}) \quad (4.43)$$

$$\zeta(T) = c_p \left[(T - T_{Amb}) - T_{Amb} \ln \frac{T}{T_{Amb}} \right] = e(T) - c_p T_{Amb} \ln \frac{T}{T_{Amb}} \quad (4.44)$$

With the assumption that horizontal cross-sectional area of the TES is constant, a horizontal element of mass dm can be approximated as:

$$dm = \frac{m}{Z} dz \quad (4.45)$$

Where Z is the total height of the tank. Since temperature is a function of height only, the expressions for e and ζ can be written as

$$e(z) = c_p(T(z) - T_{Amb}) \quad (4.46)$$

$$\zeta(z) = e(z) - c_p T_{Amb} \ln \frac{T(z)}{T_{Amb}} \quad (4.47)$$

By inserting equations 4.51 - 4.53 into equations 4.47 and 4.48, the energy E and exergy Ξ can then be written as

$$E = \frac{m}{Z} \int_0^Z e(z) dz = mc_p(T_m - T_{Amb}) \quad (4.48)$$

$$\Xi = \frac{m}{Z} \int_0^Z \zeta(z) dz = E - mc_p T_{Amb} \ln \frac{T_e}{T_{Amb}} \quad (4.49)$$

where

$$T_m = \frac{1}{Z} \int_0^Z T(z) dz \quad (4.50)$$

$$T_e = \exp \left[\frac{1}{Z} \int_0^Z \ln T(z) dz \right] \quad (4.51)$$

Physically, T_m represents the temperature of a TES when it is fully mixed. T_e expresses the temperature of a fully mixed TES which has the same exergy as the stratified TES. Generally $T_m \neq T_e$, because T_e is dependent of the

stratification of the storage. In the case where the limit condition $T_m = T_e$ is reached, the TES is already fully mixed.

The exergy difference of the stratified TES and the same TES which is fully mixed can be expressed as

$$\begin{aligned}\Delta \Xi &= \Xi - \Xi_m \\ &= E - mc_p T_{Amb} \ln \frac{T_e}{T_{Amb}} - \left(E_m - mc_p T_{Amb} \ln \frac{T_m}{T_{Amb}} \right) \\ &= mc_p T_{Amb} \ln \frac{T_m}{T_e}\end{aligned}\quad (4.52)$$

Continuous-Linear Temperature-Distribution Model

The continuous-linear temperature-distribution model is a tool to calculate the energy and the exergy of a TES which consists of k horizontal zones, in each of which the temperature varies linearly from the bottom to the top. The temperature zones can be expressed as

$$T^C(z) = \begin{cases} \phi_1^C(z), & z_0 \leq z \leq z_1 \\ \phi_2^C(z), & z_1 \leq z \leq z_2 \\ \dots \\ \phi_k^C(z), & z_{k-1} \leq z \leq z_k \end{cases} \quad (4.53)$$

where $\phi_j^C(z)$ represents the linear temperature distribution in zone j .

$$\phi_j^C(z) = \frac{T_j - T_{j-1}}{z_j - z_{j-1}} z + \frac{z_j T_{j-1} - z_{j-1} T_j}{z_j - z_{j-1}} \quad (4.54)$$

With equations 4.56, 4.57, 4.59 and 4.60 we get

$$T_m^C = \sum_{j=1}^k x_j (T_m)_j \quad (4.55)$$

where $(T_m)_j$ is the mean temperature in zone j , which is

$$(T_m)_j = \frac{T_j + T_{j-1}}{2} \quad (4.56)$$

and x_j the mass fraction for zone j :

$$x_j = \frac{m_j}{m} = \frac{z_j - z_{j-1}}{Z} \quad (4.57)$$

For the equivalent temperature we get

$$T_e^C = \exp \left[\sum_{j=1}^k x_j \ln(T_e)_j \right] = \prod_{j=1}^k (T_e)_j^{x_j} \quad (4.58)$$

with the equivalent temperature $(T_e)_j$ in zone j , that is,

$$(T_e)_j = \begin{cases} \exp \left[\frac{T_j(\ln T_j - 1) - T_{j-1}(\ln T_{j-1} - 1)}{T_j - T_{j-1}} \right], & \text{if } T_j \neq T_{j-1} \\ T_j, & \text{if } T_j = T_{j-1} \end{cases} \quad (4.59)$$

4.7.4 Example: Evaluating stratified TES energy and exergy

Within this example energy and exergy quantities are determined for a realistic temperature distribution by using the continuous linear model. The temperature distribution of the TES can be seen in figure 4.28. The TES fluid is taken to be water. Following specified data are given:

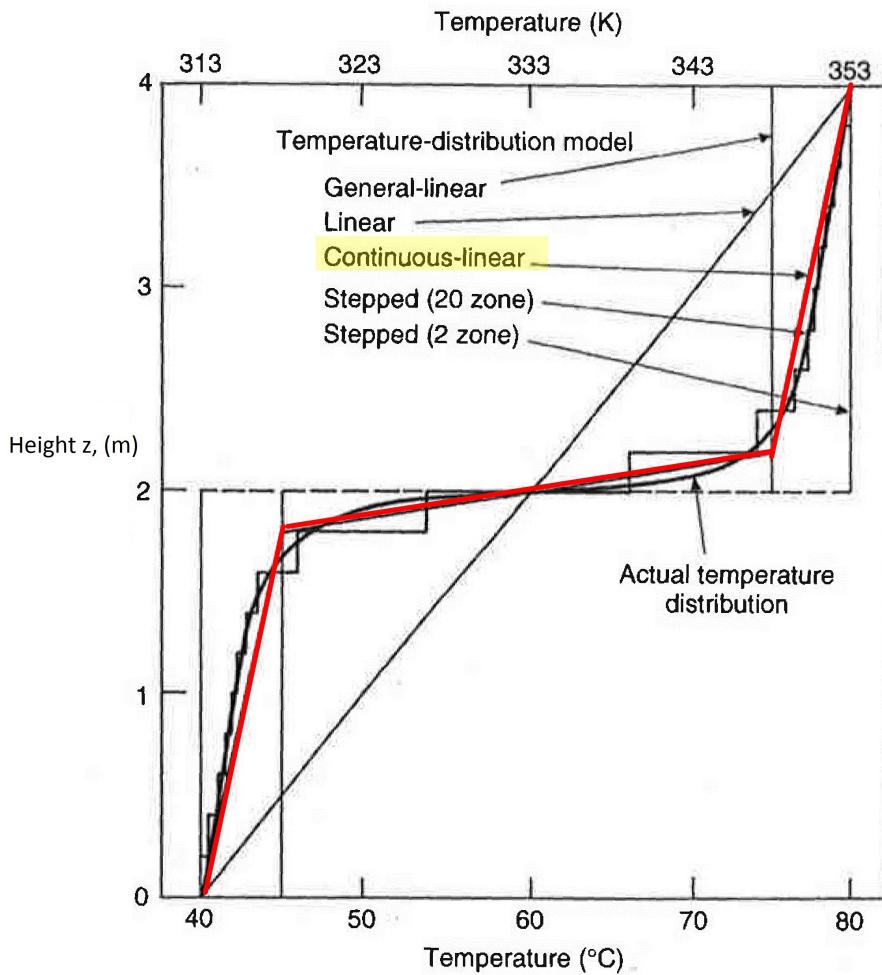


Figure 4.27: The realistic vertically stratified temperature distribution considered in the example, and some of the temperature-distribution models (continuous-linear model: red curve) [Dincer and Rosen, 2002]

The following data are given:

General data:

- Temperatures
 - At TES top: $T(z = Z) = 353 \text{ K}$
 - At TES bottom: $T(z = 0) = 313 \text{ K}$
 - Reference environment: $T_{Amb} = 283 \text{ K}$
- TES fluid parameters
 - Height: $Z = 4 \text{ m}$
 - Mass: $m = 10000 \text{ kg}$
 - Specific heat: $c_p = 4.18 \text{ kJ/kgK}$

Specified data (for the continuous linear temperature distribution model):

- $k = 3$ (Subdivision of the storage into three zones)
- $z_1 = 1.8 \text{ m}$, $z_2 = 2.2 \text{ m}$
- $T_1 = 318 \text{ K}$, $T_2 = 348 \text{ K}$

Tasks:

- a) Determine the energy capacity of the TES with respect to ambient temperature:
 - of the stratified tank E
 - of the fully mixed tank E_m
 - and the difference between those ΔE
- b) Determine the exergy capacity of the TES with respect to ambient temperature:
 - of the stratified tank Ξ
 - of the fully mixed tank Ξ_m
 - and the difference between those $\Delta \Xi$

Results:

4.7.5 Applications

TES for Domestic Hot Water (DHW) applications. Water TES for DHW production is by far the most established TES technology. Hot water tanks can be combined with a fuel-burning system, solar collectors or a district heating system.

Stratified liquid TES from Strata-Therm. The SoCool® system from Strata-Therm employs aqueous solutions as stratification fluids to provide cooling at temperatures lower than 4.1 °C. During peak cooling periods, cold fluid can be withdrawn from the bottom of the tank and returned on the top of the tank at a higher temperature. In off-peak periods, warm water can be extracted from the top of the storage tank, cooled with low cost off-peak energy and returned to the bottom of the tank for later use.

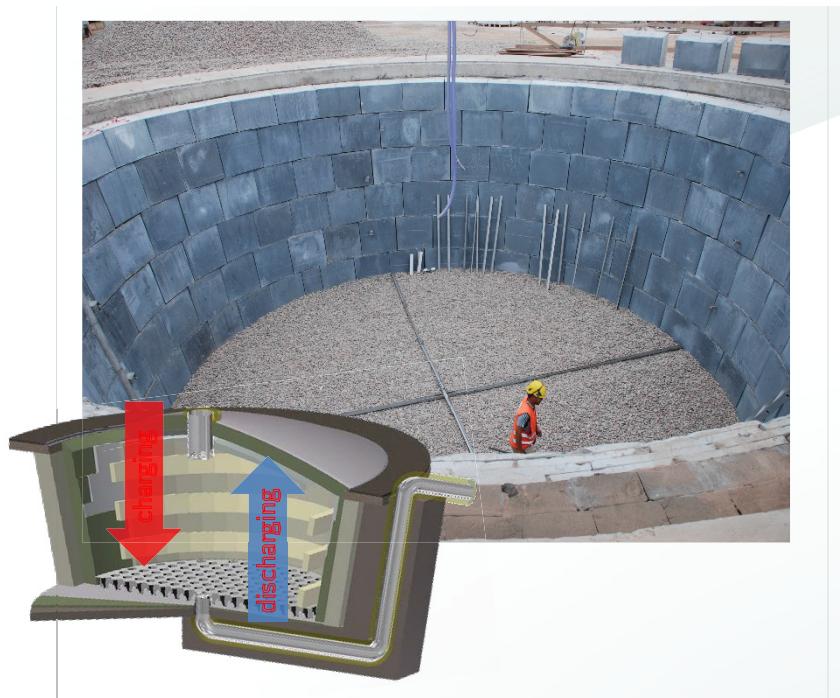


Figure 4.28: Industrial scale rock TES developed by Airlight Energy (from the presentation of Ms. Bevilacqua in SSTES 2014).

Stratified packed-bed of rocks developed by Airlight Energy. Airlight Energy has developed a high-temperature TES storage based on a packed bed of rocks. The storage can be operated at temperatures up to 640 °C and is intended for implementation in CSP and AA-CAES applications. Its main advantages with respect to molten salts systems is the inexpensive storage

medium, the direct heat transfer between the HTF and HSM which eliminates the need for additional heat exchangers and the lack of freezing issues. Figure 4.29 shows the system in industrial scale, as it is developed for a CSP plant in Morocco.

Two-tank TES with molten salts in the Gemasolar CSP plant. The Gemasolar power plant in Spain (Figure 4.7.5) is the first commercial CSP plant combining a central tower receiver with molten salt as HTF and HSM. It can deliver 19.9 MW, supplying power to more than 25'000 homes. The storage system allows it to provide electricity for up to 15 hours without sunlight (sources: nationalgeographic.com.es, qmtmag.com).



Figure 4.29: Two-tank molten salt system implemented in the Gemasolar CSP plant (from <http://www.qmtmag.com>).

4.8 Latent Thermal Energy Storage

In latent heat storage, the phase change of a material is used to absorb, store and release thermal energy. In most cases the phase change from solid/liquid is considered, but solid/solid and liquid/gas phase change can also be employed. Storage materials which are used in latent TES are called Phase Change Materials (PCM).

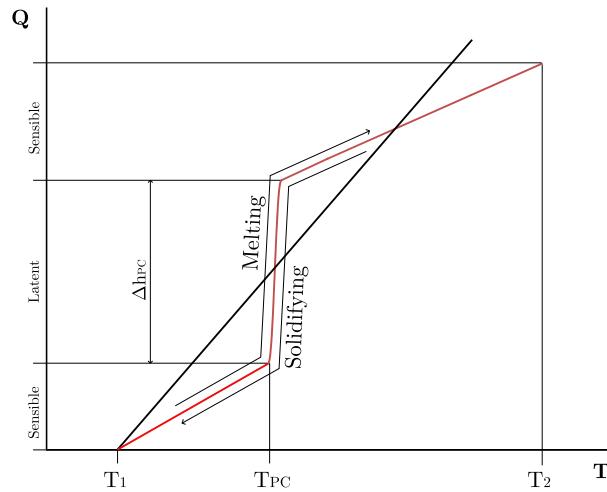


Figure 4.30: Melting and solidification processes in a latent TES cycle.

The melting and solidification processes taking place in a latent TES can be seen in Figure 4.31. For heat TES, melting corresponds to charging of the storage and solidification corresponds to the discharging of the storage. For cold TES the opposite applies. At the beginning of the melting process, the PCM is in a solid state. During the heating-up process thermal energy is added to the latent TES and the temperature of the PCM increases, storing heat in a sensible form, until it reaches the temperature where it starts to melt. This temperature is called phase change temperature (T_{PC}). If more energy is added to the TES, the storage medium starts to melt at a constant temperature, storing heat in a latent form. Once the storage medium is entirely melted, any further addition of heat will result in an additional temperature increase. The total amount of energy, which can be added to a latent TES (in other words the storage capacity) can be described with the following equation:

$$\Delta E_{charge} = U_2 - U_1 = m_{st}(c_P(T_2 - T_{PC}) + \Delta h_{PC} + c_P(T_{PC} - T_1)) \quad (4.60)$$

In the equation above T_1 is the temperature of the PCM at the beginning and T_2 is the temperature at the end of the charging process.

For the solidification, the reverse process takes place. Energy is removed from the TES and the temperature of the PCM decreases until T_{PC} is reached. Once T_{PC} is reached, the crystallisation of the PCM starts and the storage medium starts transforming from liquid to solid. This process lasts until the whole PCM is solid. If more energy is removed from the storage unit, the temperature of the now solid PCM will decrease. The total amount of energy, which can be discharged from a latent TES can be described with the following equation:

$$\Delta E_{discharge} = U_1 - U_2 = m_{st}(c_P(T_1 - T_{PC}) - \Delta h_{PC} + c_P(T_{PC} - T_2)) \quad (4.61)$$

In latent heat storage an isothermal release of thermal energy takes place in contrast to the temperature increase/decrease associated with sensible heat storage. This makes latent heat storage particularly attractive in cases where a narrow output temperature range is necessary. In a typical working temperature range, the storage capacity of latent heat storage can be 5 to 14 times greater than that of sensible storage [Salunkhe and Shembekar, 2012] which can lead to a significant decrease in the storage space requirement.

4.8.1 Phase Change Materials

As it becomes clear from equations 4.66 and 4.67, a high enthalpy of fusion is a crucial property for PCMs. Other important, desired thermo-physical, kinetic and chemical properties of PCMs are listed in Figure 4.32.

The PCM should additionally be readily available in large quantities at low cost. In practice, those criteria are not fully met by most PCMs. However, recent progress in the design and characterization of novel materials for energy storage, including nanomaterials, has opened new possibilities for enhanced performance with extended lifetimes.

In Figure 4.33 it can be seen that there are five main classes of PCM: Organic, Inorganic, Eutectic mixtures, Non-Eutectic mixtures and Phase Change Dispersions. Five of the most important PCM groups from different classes are listed in Figure 4.34 with some of their important characteristics.

The general TES temperature classification presented in Figure 4.4 also applies for latent TES. A collection of PCM material for medium temperature

Thermal Properties	Physical Properties
<ul style="list-style-type: none"> • Phase change temperature in the desired operation range • A high phase change enthalpy per unit volume • A high specific heat to provide significant additional sensible heat • High thermal conductivity of both phases 	<ul style="list-style-type: none"> • A small volume change on phase transformation • A low vapour pressure at the operating temperature • Congruent melting and solidification process • A high density
Kinetic properties	Chemical properties
<ul style="list-style-type: none"> • Low subcooling effect • A high nucleation rate • An adequate rate of crystallization 	<ul style="list-style-type: none"> • Long-term stability • Cycle-stability • Compatibility with the construction materials • Non-toxic, non-flammable and non-explosive to ensure safety

Figure 4.31: Overview of important thermo-physical, kinetic and chemical properties of PCMs.

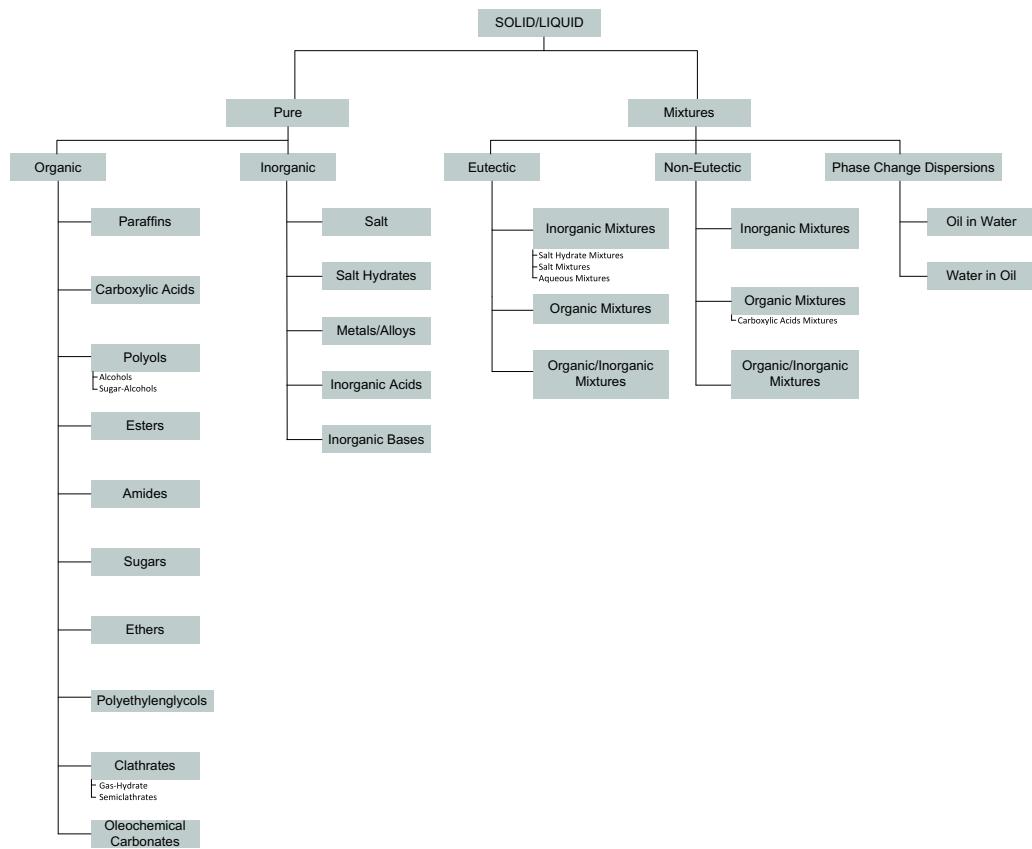


Figure 4.32: Overview of different classes of Phase Change Materials.

	Paraffins	Salt Hydrates	Carboxylic Acids	Esters	Polyols
Formula	C_nH_{2n+2} ($n = 12 - 38$)	$AB \cdot H_2O$	$C_nH_{2n+2}+O+OH$	$R-CO-O-R$	$C_nH_{2n+1}+OH$
Properties	$T_{PC} = 12 - 71^\circ C$; $\Delta h_{PC} = 100 - 250 \text{ J/g}$ organic, mixture of saturated hydrocarbons (alkanes); T_{PC} increases with the amount of atoms; most used commercial PCM	$T_{PC} = 11 - 120^\circ C$; $\Delta h_{PC} = 200 - 400 \text{ J/g}$; mixtures of inorganic salts and water; mostly used in high T; oldest and most investigated PCM	$T_{PC} = 0 - 150^\circ C$; $\Delta h_{PC} = 190 - 230 \text{ J/g}$; organic fatty acids; short-chain ($<6^\circ C$), long-chain ($>6^\circ C$); T_{PC} increases with the amount of atoms	$T_{PC} = 0 - 200^\circ C$; $\Delta h_{PC} = 120 - 200 \text{ J/g}$; generally derived from a carboxylic acid and an alcohol	$T_{PC} = 90 - 250^\circ C$; $\Delta h_{PC} = 210 - 350 \text{ J/g}$; organic
Advantages	Not toxic, not corrosive, odorless; compatible with metal containers; chemically stable; no segregation, low supercooling; paraffin mixtures can be cheap	High c_p ; high ρ ; high λ ; sharp T_{PC} ; low ΔV ; in some cases low cost; soluble in water	Low supercooling; low ΔV ; chemically stable; molecules with $C > 6$ not toxic; can be produced from natural oils; relatively sharp T_{PC}	Produced from natural sources; no subcooling; high Δh_{PC} ; odorless; low ΔV ; chemically stable; can form eutectic systems	Not corrosive
Disadvantages	Expensive; flammable; hydrophobic; high ΔV ($\approx 10\%$); low λ ; low ρ ; low viscosity; wide T_{PC} range	Corrosive for metals; high subcooling; segregation; often toxic; high ΔV ($\approx 10\%$)	Low λ ; incompatible with many materials; short-chained are often odour-intensive and corrosive; relatively expensive	Often low availability; flammable; limited information on properties; low λ ; short-chained are odour-intensive and corrosive	Subcooling; flammable; low λ ; sometimes toxic
Examples (T_{PC}, Δh_{PC})	Octadecane ($28^\circ C$, 245 J/g)	Calcium chloride hexahydrate ($29^\circ C$, 171 J/g)	Myristic acid ($58^\circ C$, 186 J/g)	Ethyl myristate ($12.5^\circ C$, 192 J/g)	Erythritol ($120^\circ C$, 340 J/g)

Figure 4.33: Comparison of important PCM groups [Sterner and Stadler, 2014], [Rathod and Banerjee, 2013], [Kleiningries et al., 2014]

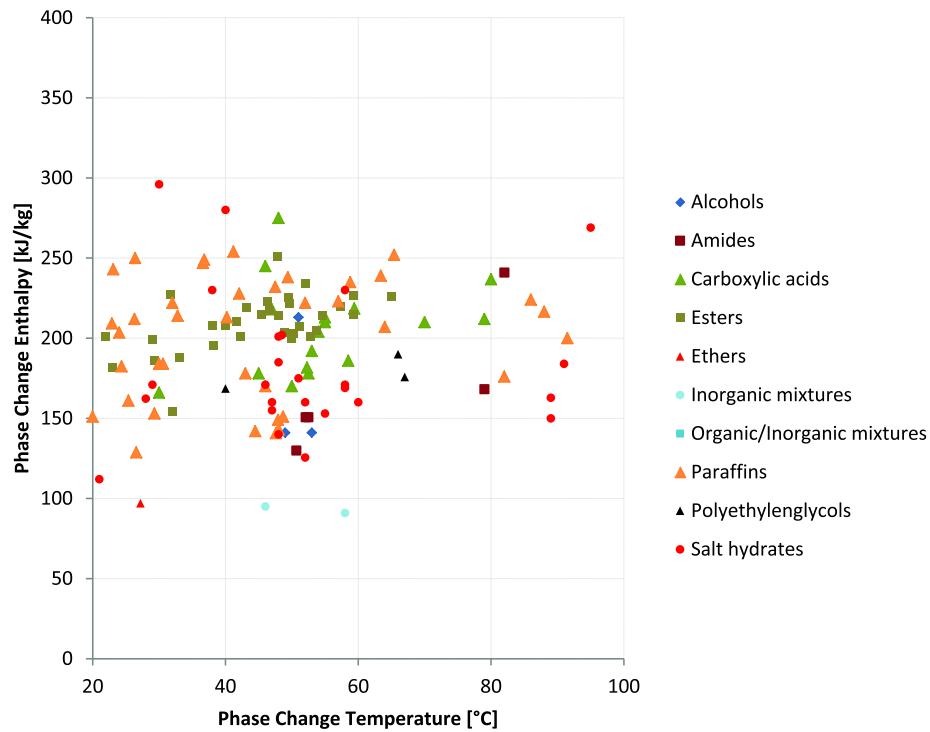


Figure 4.34: Medium temperature PCMs with corresponding enthalpy of fusion as it determined by Differential Scanning Calorimetry (DSC).

applications with their corresponding enthalpy of fusion are presented in Figure 4.35.

4.8.2 Fundamentals of Phase Equilibria and Crystallization

Pure Materials

The phase change of pure materials takes place if an equilibrium between two phases (phase equilibrium) is reached and crossed. The temperature where the phase equilibrium of a pure material occurs, depends only on the pressure. A phase diagram (see Figure 4.36), represents the lines of equilibrium or phase boundaries for a specific material, indicating the conditions, under which two or more phases can co-exist in equilibrium. The lines of equilibrium indicate the points where phase transitions occur and the space between them, the one-phase regions, where only one phase (gaseous, liquid or solid) is present. As seen in Figure 4.36 the equilibrium line between solid and liquid (so called melting line) is almost vertical, which means that the melting/freezing temperature has a weak dependence on pressure whereas the boiling point has a strong dependence on the pressure [Ulrich and Stelzer, 1992].

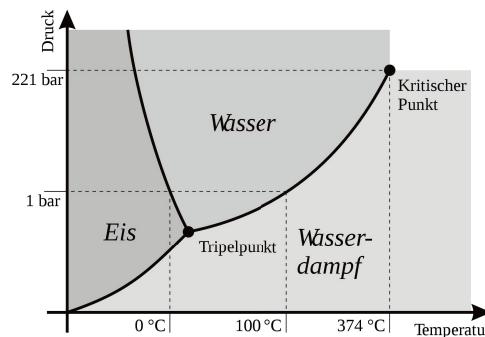


Figure 4.35: Phase diagram of water [Ulrich and Stelzer, 1992].

The crystallization of the pure material begins when the melting line is reached and the first crystals are formed and subsequently start growing. The formation of the first crystal is called primary nucleation. The primary nucleation can only take place if the liquid phase is supersaturated with respect to the equilibrium. The system is then called metastable, which means that the temperature of the liquid material is slightly below its theoretical phase change temperature. If a material reaches the metastable state, it can also be said that the material then is subcooled. Subcooling will be discussed later on in further detail.

As the first crystals are in a high energetic state, they have the tendency to dissolve back into the liquid phase. It is only when the size of the new

crystals overcomes a critical value that the clusters of solute molecules are able to grow spontaneously, giving rise to new crystals. The formation of new nuclei which results from the presence of existing microscopic crystals is called secondary nucleation. The driving force of the secondary nucleation is the temperature difference between the actual temperature of the material at its phase boundary and its (theoretical) phase change temperature.

Binary Systems

The three parameters that affect the phase equilibria of a two-component (binary) system are temperature, pressure and concentration of the components. As the pressure has little influence on the equilibria between solids and liquids, the phase changes can be represented on a temperature-concentration diagram. Binary systems can be further classified as (i) solid solution type, (ii) eutectic type and (iii) non-eutectic type.

The solid solution type is a mixture of two components, which are completely intersoluble in the liquid as well as in the solid state. Examples of solid solutions include crystallized salts from their liquid mixture, metal alloys and moist solids [Ulrich and Stelzer, 1992].

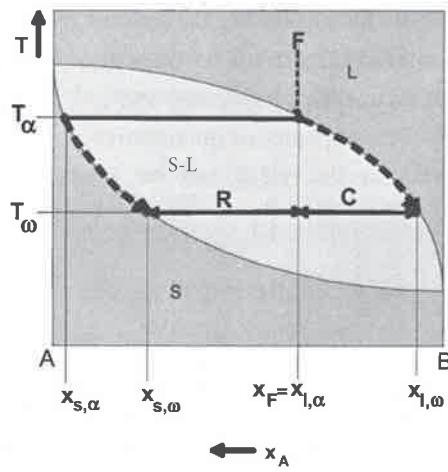


Figure 4.36: Phase diagram of a simple solid solution system [Ulrich and Stelzer, 1992].

In such systems three different areas can exist: a homogeneous liquid solution area (L), a homogeneous solid solution area (S) and a two phase area (S-L) (see Figure 4.37). The two-phase area (S-L) is limited by the melting temperature of the pure component A on the one hand and the melting temperature of the pure component B on the other hand. The liquidus line marks the minimum temperatures at which all components of the mixture are liquid. The

solidus line marks the maximum temperatures at which all components of a mixture are entirely solid. If a homogeneous liquid represented by point F and the composition x_F is cooled slowly it starts to crystallize at temperature T_α . The first crystals have the composition $x_{S,\alpha}$. As the temperature decreases further to temperature T_ω , more crystals are deposited but their composition changes successively along the solidus line to $x_{s,\omega}$ and the liquid composition changes along the liquidus line to $x_{l,\omega}$. If the composition of the crystal yields the composition of the feed ($x_F = x_{1,\alpha}$) the system is solidified totally. The average composition of the solid is the same as the feed composition at the beginning of cooling.

In eutectic systems, in contrast to the solid solution type the two components are only partially intersoluble in the solid state. Therefore in the solid state two phases exist, whereas in the liquid state the components are completely intersoluble. In such a system (see Figure 4.38), three one-phase regions (L, S_1 and S_2) and three two-phase areas ($S_1 - L, S_2 - L$ and $S_1 - S_2$) exist. At the eutectic point (EU), three phases will be in equilibrium, the liquid phase L , the first solid phase S_1 and the second solid phase S_2 . The eutectic point is characterized by composition x_{EU} and the corresponding temperature T_{EU} . Each one of the two solids forms its individual solidus line and liquidus line. The two-phase areas ($S_1 - L$ and $S_2 - L$) are limited by the melting temperature of the pure components (in this case A and B) on the one hand and the tie lines at the eutectic temperature T_{EU} on the other hand. In respect to the composition of the liquid, F_1, F_2 and F_3 , three results can be obtained as shown in Figure 4.38.

- Case 1: If the liquid at F_2 with the eutectic composition x_{EU} is cooled slowly to temperature T_{EU} there is a simultaneous formation of solid S_1 and solid S_2 . The composition of the solid state is the same as the composition of the liquid state. One material can have more than one eutectic compositions.
- Case 2: If the liquid at F_1 with the composition x_{F_1} is cooled slowly to temperature $T_{1,\alpha}$, solid S_1 starts to form. During further cooling the compositions of the solid S_1 and the liquid changes according the solidus line for S_1 and he corresponding liquidus line. If the temperature reaches the eutectic temperature T_{EU} both solids S_1 and S_2 crystallize simultaneously.
- Case 3: If the liquid F_3 with the composition x_{F_3} is cooled slowly to temperature $T_{3,\alpha}$ solid S_2 starts to form. During further cooling

the compositions of the solid $S2$ and the liquid changes according the solidus line for $S2$ and the corresponding liquidus line. If the temperature reaches the eutectic temperature T_{EU} both solids $S1$ and $S2$ crystallize simultaneously.

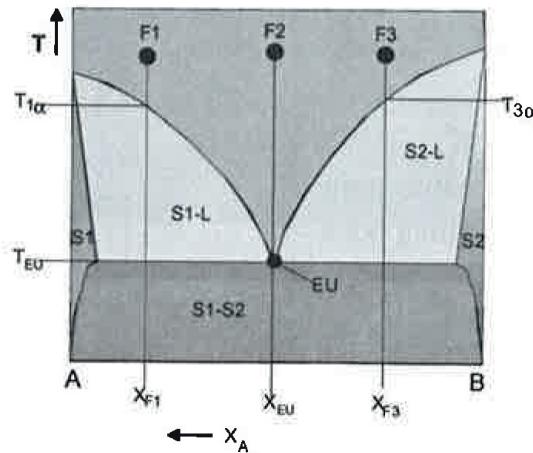


Figure 4.37: Crystallization in a simple eutectic system [Ulrich and Stelzer, 1992].

Binary Systems in Latent TES. Two-component systems are often used for latent TES applications. Eutectic mixtures are by far the most promising type because their crystallization behaviour is similar to that of pure materials. Salt hydrates, followed by fatty acids are the most popular eutectic PCM mixtures. Two main reasons make the utilization of non-eutectic mixtures for latent TES problematic: (i) there is a big difference between the temperature where the crystallization begins and the one where it is finalized, leading to loss of exergy of the latent TES and (ii) during the crystallization process, the mixture separates into two different phases, with different concentrations and densities. Due to gravitation, the phase with the higher density sinks to the bottom and the one with lower density rises to the top. This phenomenon is called phase segregation or also phase separation.

4.8.3 Heat Exchange in Latent TES

Since PCMs typically possess a low thermal conductivity [Agyenim et al., 2010], the understanding and optimization of the heat transfer processes, especially during solidification and melting, is crucial to ensure a good latent

heat storage performance. The heat transfer surface can be a heat exchanger, an encapsulation structure or even the interface between the PCM and an immiscible HTF.

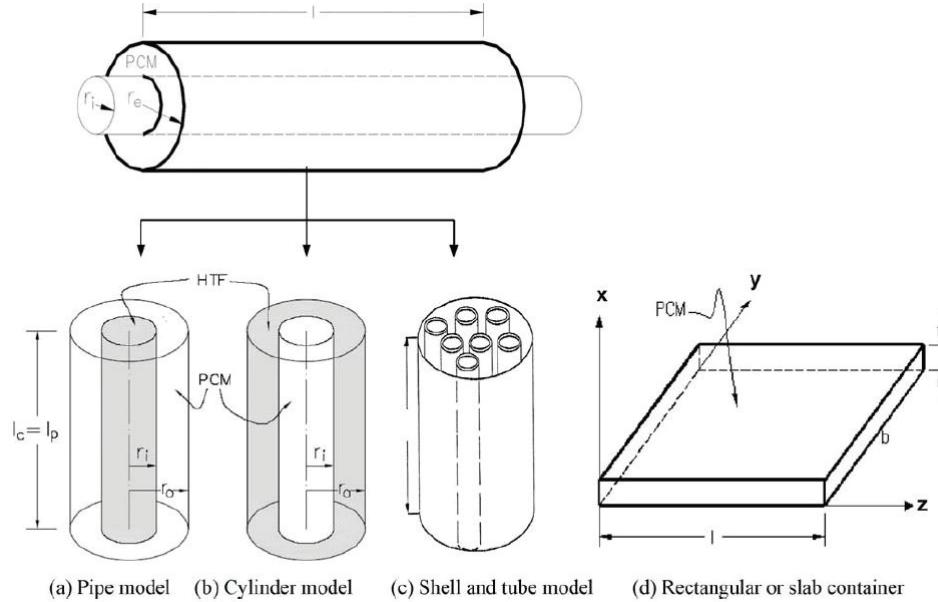


Figure 4.38: Commonly used PCM containers [Agyenim et al., 2010]

Basic Heat Exchangers/PCM Containers.

The implementation of PCM materials in TES requires a means of containment. PCM is often contained in normal bulk tanks with incorporated heat exchangers. Four of the most frequently used heat exchangers/PCM containers can be seen in Figure 4.39. Figure 4.39a shows the pipe model, where the HTF flows in the central pipe and the PCM occupies the space between the shell and the pipe. In Figure 4.39b the cylinder model is shown, where the PCM fills the central tube and the HTF flows parallel to the tube between the tube and the shell. A study comparing the two systems [Agyenim et al., 2010] recommends the pipe model because it can provide a shorter melt time and suffers less heat losses to the environment. A third variation is the shell tube system (Figure 4.39c) which is often used to improve the heat transfer of the LHS. Heat transfer in the shell and tube system is dominated by multiple convective heat transfer in contrast to conduction in the case of the pipe model ([Agyenim et al., 2010]), and can significantly reduce the charging period of the LHS.

Flow Direction.

Two types of HTF flow can be employed in a cylindrical container. In the par-

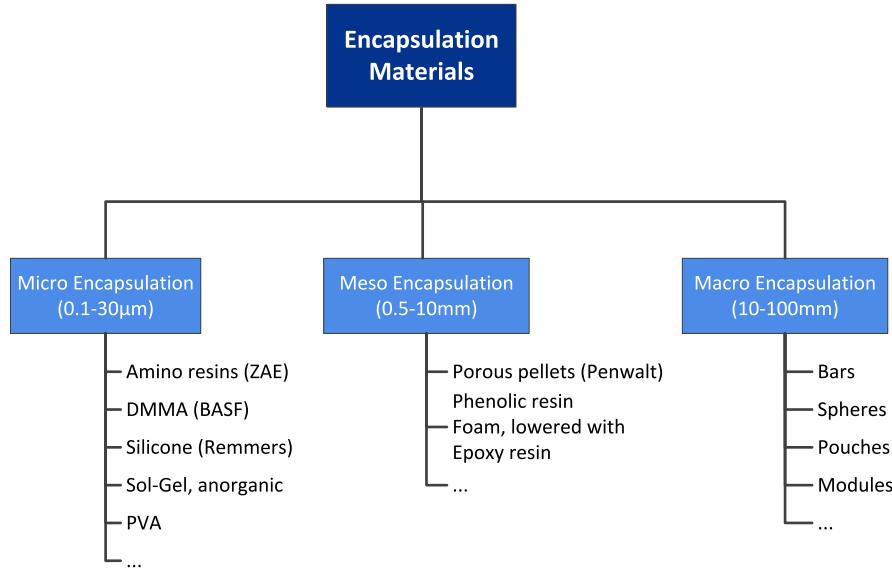


Figure 4.39: PCM encapsulation types and common materials

allel flow the HTF is introduced from the same side in both charging and discharging. In the counter-current flow, the flow changes direction during charging and discharging, so the hot and cold fluid enter from the opposite ends. Studies have shown that the parallel flow can increase the charge/discharge rate and reduce supercooling ([Agyenim et al., 2010]).

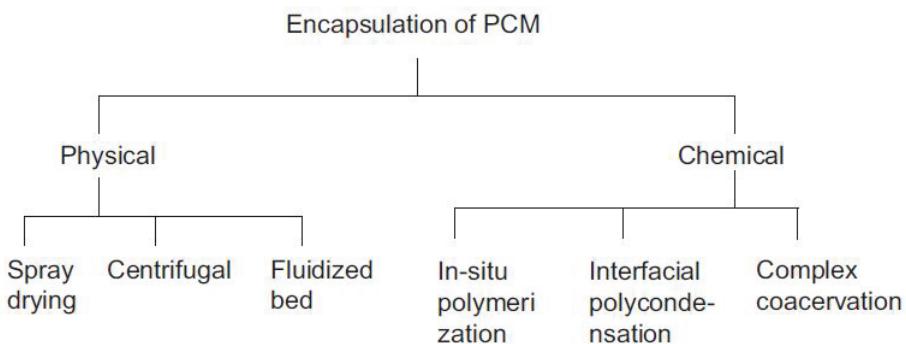


Figure 4.40: Production methods of microencapsulated PCMs [Salunkhe and Shembekar, 2012]

Encapsulation.

As already discussed, PCMs are often enclosed in bulk tanks with incorporated heat exchangers to realize heat transfer. Alternatively, PCMs can be

Trademark name/ Industry	PCM (s)	Shell material (s)	Container (s)	Average container size	Application (s)
Cristopia	Eutectic salts	Polyolefin	Spherical balls	77 mm	Industrial refrigeration, building conditioning
ClimSel/climator	Sodium acetate, sodium sulphate	-	Pouches	-	Medicine transportation, clothing, air-conditioning, electronic cooling, fire protection
Rubitherm	Paraffin, salt hydrate in granulate, powder and compound forms	Aluminum, plastic	Box, bag	-	Storage and transport of food, medical equipments, storage materials for textile
Latest™/ TEAP Energy	Glauber's salt, soda ash, sodium acetate and paraffin wax	Aluminum, steel and polyethylene	Bottles, balls	25.4 mm	Hot pads and solar heating, telecom enclosure, back-up air-conditioning, cold storage
PCM Products Ltd.	Eutectics, salt hydrates, organic materials, and high temperature salts	Rubber, HDPE plastic	Tube, ball, pouches, plate	40 mm	Space International space station, automotive passive cooling, solar heating and heat recovery
MPCM/Microtek Laboratories Inc.	Paraffin	polymer	-	17–20 µm	Active wear clothing, woven and non-woven textiles, building materials, packaging, and electronics
Micronal®/BASF	Paraffin wax	Polymer	Microcapsules impregnated with gypsum wall boards	5 µm	Building conditioning, surface cooling
DuPont™ Energain™ Aegis	Paraffin wax	Aluminum	Wall panels	-	Building conditioning, fire protection
	Inorganic salts	High density polyethylene	Panels, spherical balls, pouches	75 mm ball dia, 145 mm × 260 - mm size pouch	Cold storage, boilers, solar water heaters, transport of blood, frozen food, fruits and vegetables etc.

Figure 4.41: Commercial encapsulated PCMs with respective manufacturer and applications [Salunkhe and Shembekar, 2012]

packaged in smaller-size sealed containers that also serve as the heat exchange area. This encapsulation structures are classified according to their size to micro-, meso- and macro-capsules, as seen in Figure 4.40.

Some of the main functions of PCM encapsulation are: (i) to avoid material exchange between the PCM and its surroundings in order to avoid harming the surroundings or change the PCM composition, (ii) to facilitate heat transfer by increasing the surface to volume ratio, (iii) to help avoid segregation and (iv) to give desired shape/size to the PCM. However, encapsulation might lead to significant challenges such as: (i) increase in subcooling, especially in the cases of micro- and meso-encapsulation, (ii) high increase in cost and (iii) low cycling stability [Salunkhe and Shembekar, 2012].

The packaging material should (i) serve as an effective barrier between the PCM and the environment, both preventing material loss from the inside (e.g. water loss in the case of salt-hydrates) and if necessary penetration of external components (e.g. oxygen), (ii) have a high heat conductivity, (iii) be chemically compatible with the PCM, (iv) be mechanically (withstand thermal stresses and volumetric changes of PCM) and chemically stable and (v) be easy to handle. Containers for macro-encapsulation are mostly metallic (e.g. tin, copper, steel) and plastic (e.g. polyethylene, high-density polyethylene, polypropylene). Metallic packaging is used for high temperature applications and to enhance heat transfer. Several structures are being used such as bars, spheres, pouches. As seen in Figure 4.41, there are two main techniques for the production of microencapsulated PCMs. Physical methods

generally result in larger sizes and rougher surfaces in comparison to chemical methods [Salunkhe and Shembekar, 2012]. Macro-encapsulated PCMs are the most widely used but micro- and mesoencapsulated PCMs are also produced on an industrial scale. Figure 4.42 lists some important encapsulated commercial products for various latent heat storage applications.

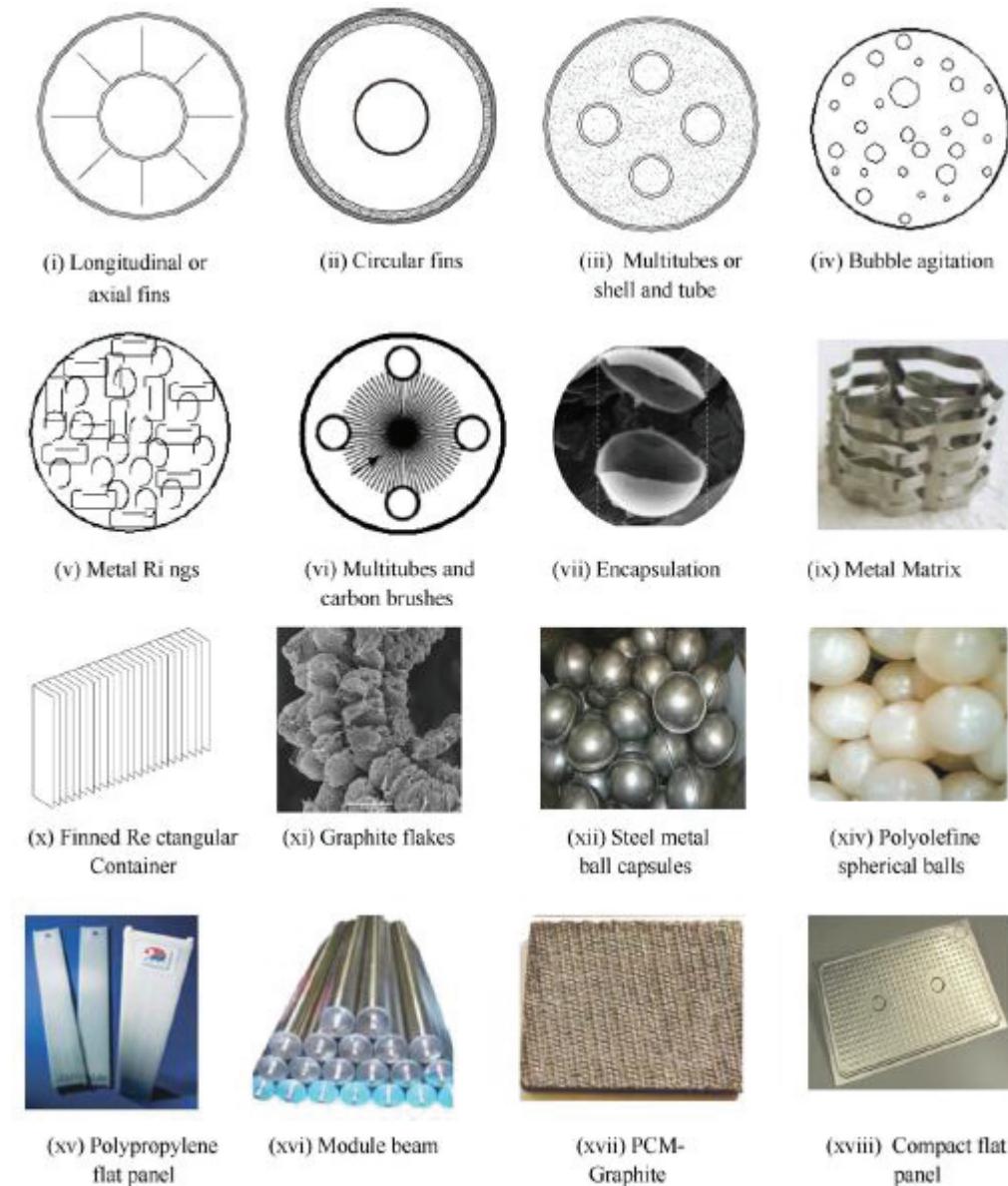


Figure 4.42: Configurations for enhancement of heat transfer in latent heat storages [Agyenim et al., 2010]

Configurations for Heat Transfer Enhancement.

In the cases where the basic storage configurations do not result in acceptable heat transfer rates or are not applicable for practical reasons, more sophisticated configurations can be employed. A list of important configurations for the enhancement of the heat transfer in LHS, is shown in Figure 4.43. An important note is that irrespective of the PCM used, the employment of any of the techniques listed will lead to an increase in the charging/discharging rate of the storage [Agyenim et al., 2010]. Probably the most often utilized method is integration of fins in the PCM. The advantages of this method are its simplicity, low construction cost and ease in fabrication. Another popular method is the impregnation of a highly conductive metal matrix into the PCM. A study showed that adding lessing rings in a paraffin storage increased the effective thermal conductivity by an order of magnitude, from $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ to $2 \text{ W m}^{-1} \text{ K}^{-1}$ [Agyenim et al., 2010].

4.8.4 Challenges with latent TES

Despite the high energy density and other promising properties PCMs, there is still a lot of challenges to be addressed before latent TES can become widely commercially available. This subsection presents the most important issues associated with latent TES.

Subcooling

Many PCMs do not solidify immediately upon cooling below the melting temperature, but start crystallizing only after a temperature well below the melting temperature is reached. This effect is called subcooling and can be observed in Figure 4.44). In most cases, subcooling is not desired in a latent TES. The presence of subcooling makes it necessary to reduce the temperature of the PCM well below the phase change temperature to start crystallization and to release the latent heat stored in the material. This results in energy and exergy efficiency losses of the storage system. In extreme cases, the solidification of the PCM might not occur at all, making the extraction of the stored latent heat impossible. In this case the material will only store and release sensible heat. During the melting process there is no such effect like subcooling, which means that the material starts to melt as soon as the material reaches its phase change temperature. Subcooling is not only a material property, but also a system property. Certain materials have a higher tendancy to subcool than others. For example highly pure water can be cooled down to temperatures as low as -25°C for the nucleation process to start.

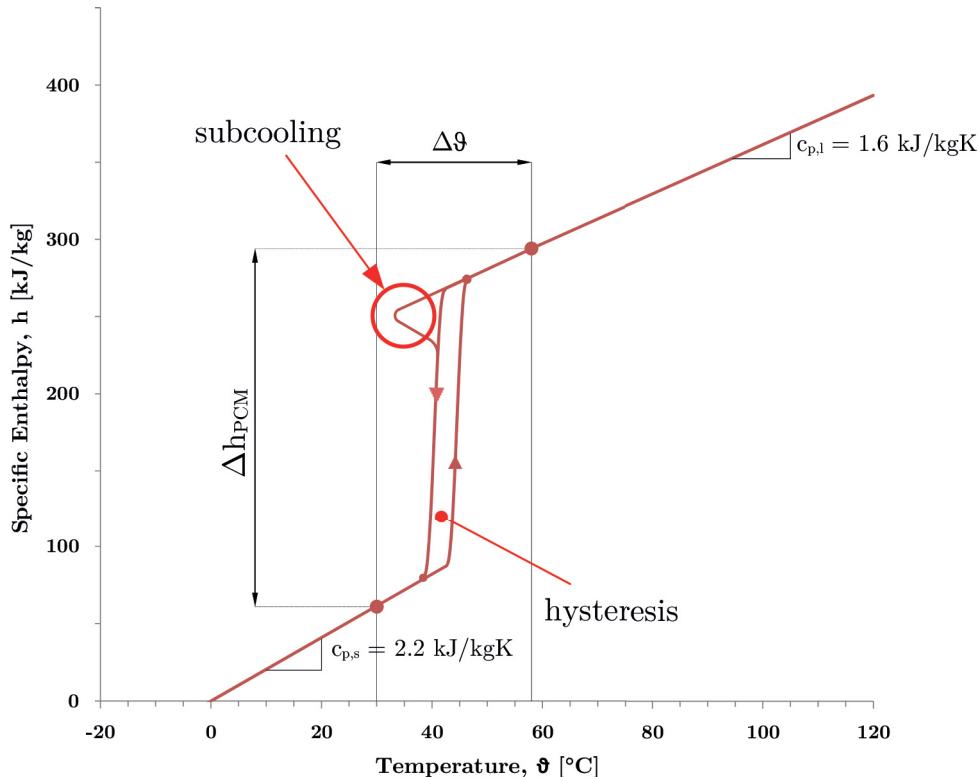


Figure 4.43: Evolution of the specific enthalpy of a PCM with temperature.

The degree of subcooling depends on a number of factors [[Mehling and Cabeza, 2008](#)]:

- Type of the material (size of the materials).
- Purity of the material.
- Surface of the heat exchanger.
- Surface of the surrounding material.
- Volume of enclosed PCM.

Some methods that are employed to reduce subcooling are:

- Induction of mechanical stress, shock wave.
- Seeding (adding crystals of the PCM material).
- Addition of a nucleating agent to cause heterogeneous nucleation.

- Creation of a local cold spot to induce homogeneous nucleation at temperatures below the freezing point.
- Electrical activation.

One can see in Figure 4.44 that there is a difference between the apparent melting and crystallisation temperature ranges. The effect is called hysteresis and can be influenced by a number of factors, such as: heat transfer effects from the heat source/sink to the PCM (apparent hysteresis), subcooling, kinetic effects (very slow rate of latent heat) as well as formation of different crystalline structures during phase change. The melting temperature range for all materials than the crystallization temperature range. It is therefore important to keep in mind that materials have a range of phase changing temperatures, rather than one single temperature.

Phase Segregation

As mentioned before, phase segregation leads to the separation of a mixture into its components. If separation occurs, the local concentration of the substances doesn't correspond to the eutectic point anymore. As a consequence, the storage is characterized by a range of phase changing temperatures instead of one uniform one, which don't correspond to the design charging and discharging temperature of the TES. In such cases only a small part of the melting/solidification heat can be absorbed/released and therefore only a small fraction of the storage capacity can be utilized, severely reducing the energy density of the storage.

In order to avoid phase segregation, the separation of the crystals of the different components has to be avoided despite their typically varying densities. Some methods used to avoid phase separation are listed below [Mehling and Cabeza, 2008].

- Addition of thickening agent to increase the viscosity.
- Chambering, meaning enclosing the PCM in small volumes, preventing the separation of the components.
- Continuous artificial mixing to remix separated phases and ensure the homogeneity of the blend.

Low heat conductivity. As already discussed, PCMs are typically characterized by low thermal conductivities which makes the delivery of high

powers challenging. In order to address this issue, enhanced heat transfer structures are being developed (see Figure 4.43). Research has shown that great potential for heat conductivity enhancement, lies also in the dispersion of high conductive particles in the PCM itself [Chiu, 2013].

Other challenges. PCMs can be corrosive and reactive with different types of materials. Therefore, great care should be taken during the choice of the equipment in contact with the PCM (e.g. container, heat exchanger) to ensure the compatibility and therefore the proper operation and long-life of the TES. Volume change and high flammability are two more issues that impose constraints to the choice of TES containers and heat exchange structures.

4.8.5 Applications

Table 4.4: Currently known commercial PCM manufacturers [Agyenim et al., 2010]

Manufacturer	PCM temperature range	Number of PCMs listed
RUBITHERM (www.rubitherm.de)	-3 °C to 100 °C	29
Cristopia (www.cristopia.com)	-33 °C to 27 °C	12
TEAP (www.teappcm.com)	-50 °C to 78 °C	22
Doerken (www.doerken.de)	-22 °C to 28 °C	2
Mitsubishi Chemical (www.mfc.co.jp)	9.5 °C to 118 °C	6
Climator (www.climator.com)	-18 °C to 70 °C	9
EPS Ltd (ep-sltd.co.uk)	-114 °C to 164 °C	61

Latent heat storage technologies are mostly still in a research/pilot plant

demonstration phase but there are already some commercial manufacturers that have introduced PCMs in the market. A list of the known manufacturers is provided in Table 4.4.

Ice Storage is by far the most vastly applied and economical type of latent TES. It is typically used for cooling and air-conditioning applications to reduce the electricity consumption at peak hours and the size of the cooling machines (see ice storage case study).

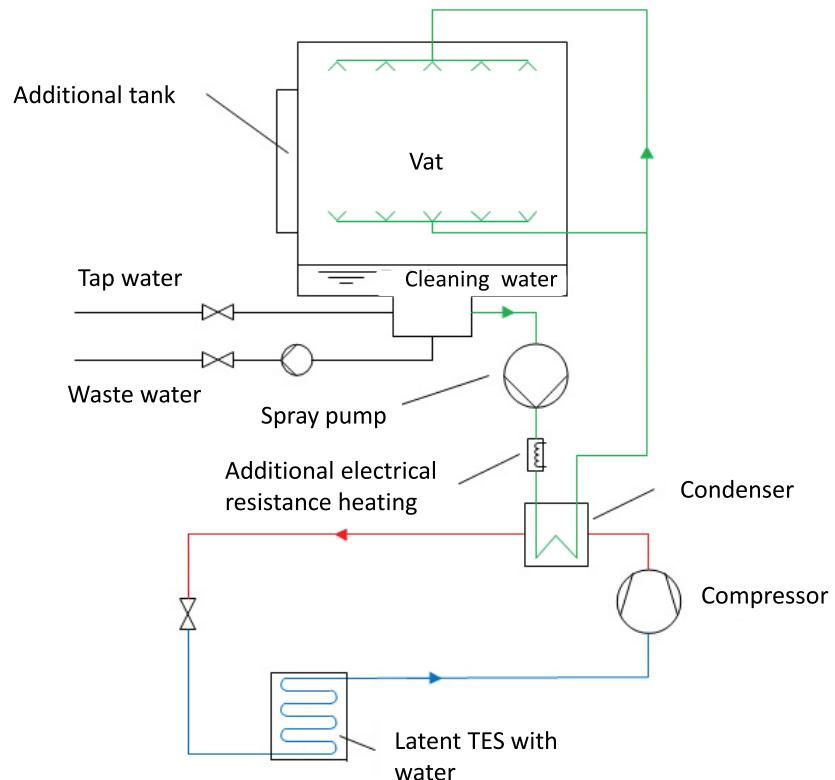


Figure 4.44: Schematic of a dishwasher with integrated latent TES, developed for V-ZUG AG (source: CTI Proposal, V-ZUG AG - HSLU T & A).

Dishwasher with PCM. The company V-Zug in collaboration with HSLU, developed a dishwasher with an integrated heat-pump and latent TES (Figure 4.45). The heat pump supplies the required heat for the process. The heat source for the heat pump is the heat released from a latent TES with water as HSM. The use of a latent TES ensures that there is enough heat delivered to the heat pump, despite the limited available space. The

specific heat that water absorbs from the environment during melting which can be supplied to the heat pump during solidification is 330 kJ/kg which corresponds to 92.6 kWh/m³. The only disadvantage of water as a HSM is its low crystallization temperature which reduces the COP of the heat pump. A PCM with a phase change temperature in the range of 10-15 °C would result in a more efficient process.

Constant transport temperature. There are numerous applications, where a product has to be locally transported without a reduction in its temperature. An example are catering-services. Meals have to be transferred from the producer to the consumer at an almost constant temperature, which makes this application ideal for the implementation of PCM. One product developed by the company Rubitherm GmbH is the "Pizza heater". The "Pizza heater" is a container with integrated PCM which has enough room to allocate the pizzas that need to be transported. The PCM stores the heat released in the beginning by the hot meal and supplies the heat later when the temperature starts to drop. The meal temperature can therefore stay almost constant over a long period of time, allowing for long transportation distances. Other applications for temperature-controlled packaging is the shipping of vaccines and medical supplies.

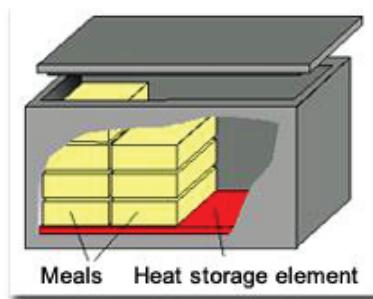
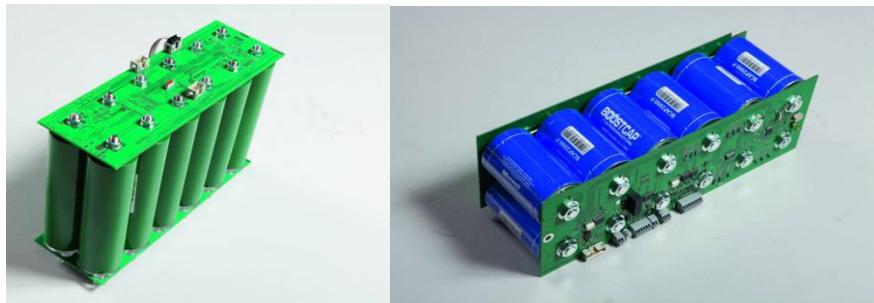


Figure 4.45: Pizza heater from the company Rubitherm GmbH (source: www.rubitherm.com).

5. Storage of Electrical Energy



5.1 Motivation, Typical Questions and Teaching Aims

5.1.1 Motivation and Typical Questions

In future, the question of energy storage in relationship with the energy supply will play an essential role. On one hand, storage systems are needed due to the expanding decentralized energy production. On the other hand, this currently relevant topic is characterized by the oil shortage which contributes to a quick growth of E-mobility. Beside the integration of the new, decentralized renewable energies, energy storages represent one of the main challenges. In addition, they play an important role for the so called “new mobility”. The highest innovation rates are made within this topic. Those are the reasons to not only give you an overview of battery and supercap technologies, but also of the charging management and the integration options. Supercaps, which are not well known yet, are part of this lecture, as they, together with Li-ion batteries, are going to increase in importance, the topic can be defined asking the following five questions:

1. Which storage technologies and applications fit together and when are they economically reasonable?
2. How do we have to design storage systems? Where do we begin and which key figures have to be specified?
3. How can we realize a BMS (Battery Management System) and which tasks should it be able to perform?
4. Which integration tasks have to be solved?
5. How do we measure storage systems?

5.1.2 Teaching Aims

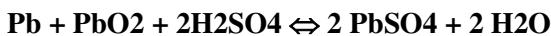
1. Knowing the opportunities of energy storage systems and being able to list two advantages and two disadvantages of each specific application.
2. Knowing the key facts/characteristics of data sheets, how to read and interpret them.
3. Knowledge of basic charging methods.
4. Being able to design simple Li-ion storages and super-caps as well as having the expertise to verify data using measurement devices.
5. Knowing how to provide necessary profiles for the storage specification.
6. Being aware of the differences between the integration of accumulators and supercaps and being able to name important and essential requirements.
7. Having the skills to describe the importance of energy storage systems for today's modern applications using only five sentences.

5.1.3 Important Terms

Accumulators	Rechargeable batteries in strict sense of the word.
Batteries	Electrochemical energy storages, general term. Sometimes, the term “battery” is also used for accumulators. The differentiation is more common in German.
C	Unit of the discharging current. 1C means, that the discharging current is as high as the defined load capacity [Ah]. 3C means that the current is three times as high as for 1C. C5 is only a fifth of the 1C current. Consequently, the discharge would last 5h.
CC	Constant Current, Charging method that uses a constant current.
CCS	Computer Charge System, Charging method based on a µController, which continuously models the inner battery state and should therefore exactly determine the whole loading state independent of the exemplar in use. Some CCS chips already exist.
CV	Constant Voltage, Charging method that uses a constant voltage.
Primary Cells	Non-rechargeable batteries, energy out of single chemical reactions!
Secondary Cells	Electrically rechargeable cells, electricity is a secondary energy form!
Shallow Cycles	Partly loading, discharge of max 5-20%.
SoC, DoD	State of Charge, Depth of Discharge in %.
Supercapacitors	Ultracapacitors, EDLC (el. double layer capacitor), electrical capacitors that are used as energy storages which have an extremely high capacity, but mostly a voltage limitation (typ. 2.5V) at the same. Helmholtz was the inventor.
Thermal runaway	Thermal, positive feedback, especially for Li-ion batteries. The heating leads to even more heating and finally the battery explodes.
Complete cycle	A complete cycle is defined as a complete discharging- followed by a charging-cycle according to the data sheet.

5.2 Battery Storage Technologies

5.2.1 Pb Batteries

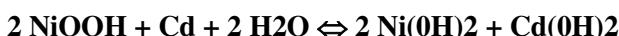


Advantages	Disadvantages
<ul style="list-style-type: none"> - Low price because high # of pieces - Available in many different types - Well recyclable 	<ul style="list-style-type: none"> - Slight specific energy <ul style="list-style-type: none"> - Not allowed for deep discharging - Low lifespan - Temperature sensitive - Partially maintenance is necessary

Remarks:

- Widely used
- 1st EVs equipped with this type; today in every car as board battery 12V
- Uninterruptible Power Supply (UPS)
- Different configurations for different application areas
- Types without support
- Acid has to be refilled periodically
- Typically 50-500 cycles

5.2.2 NiCd Batteries



Advantages	Disadvantages
<ul style="list-style-type: none"> - High capacity, fast charging - Low temperature compatibility - High # of cycles (1000- 4000) - Capacity widely independent from discharge current - Low dischargeability 	<ul style="list-style-type: none"> - High temperature sensitivity (> 45 °C) - Memory effect - Effects on the environment, Cd, Cd(OH)₂ is toxic - Highly self discharging - High price (3-5 x more than lead acid) - Bad efficiency (in full cycle use)

Remarks:

- Memory effects due to the forming of crystals
- Charging with 0.1C to 4C

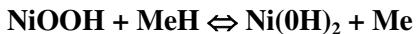
While discharging Nickel-Cadmium batteries, the voltage is almost constant over a long period of time before it suddenly collapses. This effect has to be taken into account particularly for series connections.

Memory effect: two processes:

1. Crystallization: While charging a NiCd accumulator, cadmium micro-crystals are formed. If the accumulator is discharged only to a defined state which stays constant, the effect of the formation of larger crystals out of micro crystals in unloaded areas is benefited. Consequently the surface is reduced and the crystals react worse while discharging, which results in a voltage drop.
2. Recrystallization: Past charging technologies ignore the load level of the accumulator. Charging takes place over a defined period and thus, partly discharged accumulators are overloaded. As a consequence, recrystallization at the Cd electrode occurs. This effect results in a lower output voltage due to its position within the electrochemical series and therefore a reduced capacity.

By discharging the accumulator until its end point voltage and an adjacent charge (reset loading), the original capacity is almost retrieved and the memory effect can be withdrawn.

5.2.3 NiMH Batteries



Advantages	Disadvantages
<ul style="list-style-type: none"> - High energy density - Fast chargeable - Ecological - Low costs - High lifespan 	<ul style="list-style-type: none"> - Low power density - Memory effect (compare NiCd) - High self discharging - Low temperature - Similar price as NiCd - Worse than Li-Ions (energy density)

Remarks:

- Memory effects due to forming crystals
- Similar chargeable as NiCd Cells. Therefore, the same charging method can be used because the declining ($-\Delta V$) at the point of full load is lower than the one of the NiCd cells. Here, charging is already stopped when the voltage declines only by 0.25% (instead NiCd 1%).

5.2.4 NaS Batteries

The sodium/sulfur battery differs substantially from the well-known batteries: the electrolyte consists of a solid state body, the reactants are liquid and their operating temperature is at about 300°C. Sodium and sulfur are stored liquid in closed containers and are separated from each other by a ceramic electrolyte which conducts the sodium ions and isolates the electrons.

5.2.5 NaNiCl Batteries

A big opportunity for sodium/nickel chloride batteries is seen in the auto industry. They have a power density of 100 Wh/kg at an operating temperature of 300°C and the permission of 600 load cycles

AEG → MES-DEA (CH) → FZ SoNick (Stabio, CH)

Remarks: → High Level of Integration !

Advantages	Disadvantages
<ul style="list-style-type: none"> - low costs - constant open-circuit voltage - fully dischargeable - maintenance free - partly overcharge- and overdischargeable - battery cooling having only a slight volume flow 	<ul style="list-style-type: none"> - small specific power - inner resistance is not constant - constant energy supply for the temperature control of the battery during standstill - not available

5.2.6 Li-Ion Batteries

- LiIon batteries are THE future; high research activities all over the world. Daily: new ideas, technologies and products.
- Advantage: high cell voltage of 3.6V as well as high energy density.
- Today partly competitive to supercapacitors concerning power density
- Positive voltage behavior during discharging
- Disadvantages: Safety (thermal runaway), price, availability of modules on the market, high number of cells for traction batteries!
- Trade-off between characteristics of different types of LiIon batteries!
- Emobiles: definition of cycle numbers: end of cycles is reached when the accumulator has only 80% of its starting capacity (Ah) left.
- As not only the development proceeds extremely fast, but also it is a complex topic, I resign to explain technical details such as processes etc. and limit myself by explaining the background until the current situation.

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5.2.7 Redox-Flow Batteries

Remarks:

- Charging means changing the electrolyte
- Like gas stations!
- But energ density < LiIon (70Wh/l)

5.2.8 Liquid Metal

Remarks:

- New in discussion (AMBRI)
- Low costs
- Lifespan (10'000cycles → degradation 2%)
- Safe and flexible

5.3 Other Possibilities for storing electrical energy

5.3.1 More storages

Further possibilities of storing energies: → see script chapter 2!

5.3.2 Flywheels

Flywheels may be resumed as follows:

- Low speed: <6000rpm
- High speed: > 10000rpm...1 Mio rpm → better power/denisty
- 1000Euro/kWh
- 250°C → no PMSM Motor (magnets)
- Average lifetime of 18 000 hours
 - high speeds of up to 25 000 rpm
 - support of gyroscopic forces
 - support of vehicle accelerations
 - support of mass imbalance forces

Method for striving for the highest energy content:

- High angular velocity
→ High demands on bearings
- Carbon bandage
→ Restricted heat transfer

Method for reduced self-discharge:

- Vacuum housing
→ No convection for electric machine

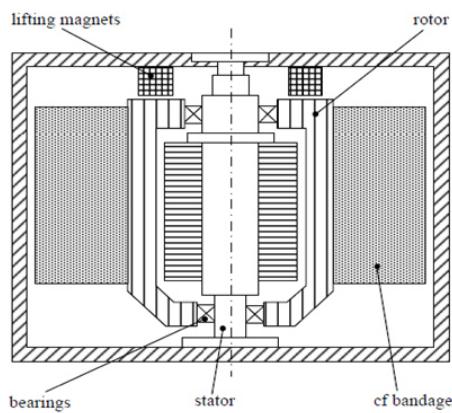


Fig. 4. Cross section of the initially proposed topology

Buchroithner, TU Graz 2012

Figure: Overview flywheels

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5.3.3 High Energy Storages: Hydro Pump Storages and others

On the high voltage level following high energy storages are used:

- Hydro pump storage plants
- Compressed Air Energy Storage (CAES)
- Thermal-electrical storages (TESS)

e.g. Water power upgrade: EWO Kaiserstuhl“ (CH: lake of Lungern)

→ leading water to a turbine first, instead of directly feeding it into the pumped-storage plant of Lungern!
Energy earnings: 12 GWh per year = ca. 2'700 households; (+45%)

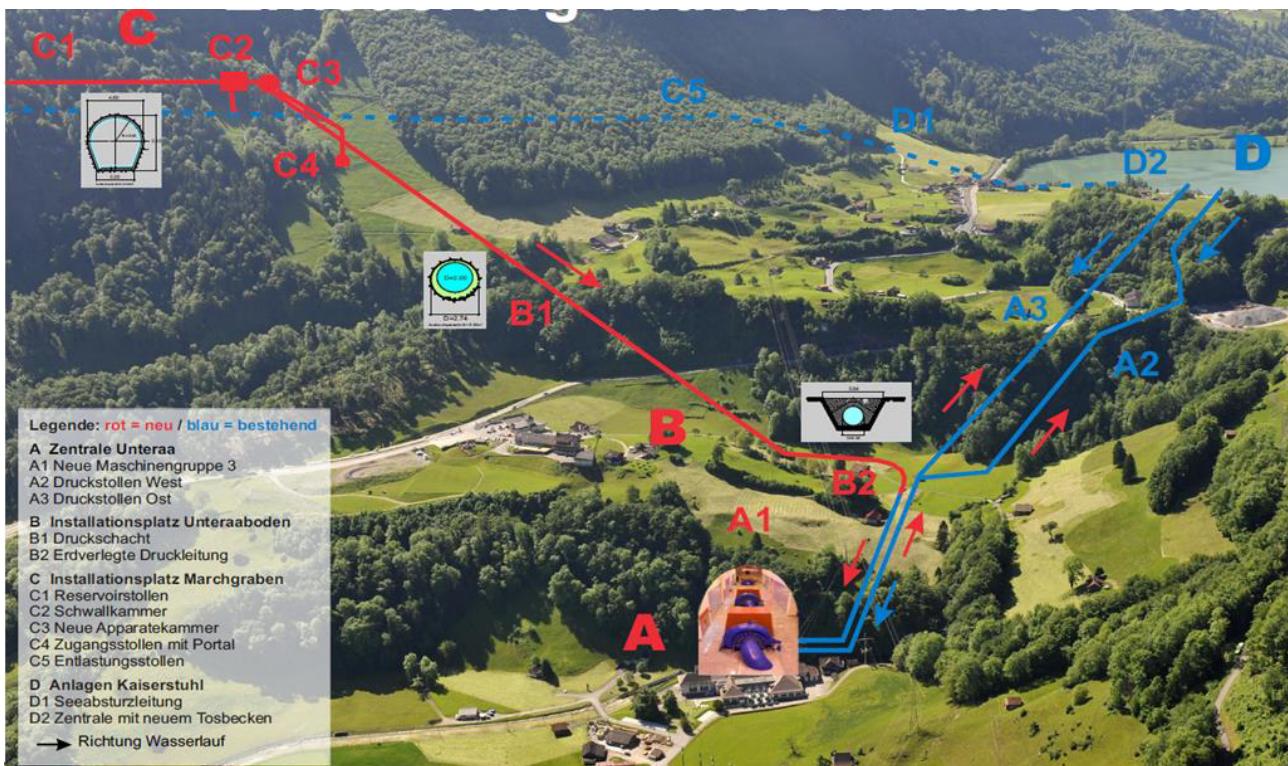


Figure: hydro power plant / pump storage upgrade lake of Lungern (CH)

5.4 Application and Design of Energy Storages

5.4.1 Key Attributes

The battery **voltage** results of the addition of all voltage components of each single cell that are connected in series. Some battery types are even delivered as single cells.

- The **nominal voltage** indicates the nominal voltage value of the battery and is normally lower than the open circuit voltage.
- The **open circuit voltage** is measured if the battery is not drained. After charging or discharging, it takes some time until the open circuit voltage remains constant. Thanks to the open circuit level, the load level of many batteries can be estimated. For supercaps, the open circuit voltage can change due to the relaxation effect.
- The **discharge voltage** defines the point up to which the battery can be discharged without being burdened. This voltage specification often goes hand in hand with a specific discharge current such as 200A for 0.8V/cell.
- The **capacity** [kWh, Ah] is the most important specification of a battery and often depends on many different parameters. The capacity can be distinguished in different capacity specifications as well. The nominal capacity is defined as the amount of energy that can be withdrawn from a battery within a clear discharge time. Furthermore, the so called extractable energy is often used. For many batteries, the extractable capacity is dependent on the discharge current which corresponds to the discharge time (also see Peukert factor).
- **Lifespan, cycles:** The result of endurance tests using laboratory conditions, where the batteries have to perform exactly defined charge and discharge cycles, is called storage life. The lifespan is dependent on the depth of discharge. A complete cycle contains a discharge until the allowed discharging border and a following full charge.

For example, lead acid batteries are only allowed to be discharged until 20% of their residual capacity, whereas NiCd batteries have to be fully discharged every now and then due to the memory effect. The lifespan is normally described using complete cycles.

- The **energy density** [Wh/kg] specifies the energy amount per mass.
- The **power density** [W/kg] specifies the power per mass that can be withdrawn. This is an extremely important parameter for the description of the ability to absorb power peaks (e.g. to regenerate braking energy while driving a vehicle). The definition for supercaps is as follows: $P' = \frac{U^2}{4 \cdot R_i}$.
- The **operating temperature** [$^{\circ}\text{C}$] describes the environmental temperature that surrounds the battery (for non-isolated systems). At deep temperatures, many battery systems lose a lot of capacity. The description: “capacity of 60% at 0°C ”, serves as an example. Li-ion batteries are not well chargeable at temperatures below $0^{\circ}\text{C}!!$

For hot batteries, such as NaS or NaNiCL, the temperature specification belongs to the inside of the battery, e.g. 300°C . This temperature is independent of the environmental temperature, as it is regulated separately. If the heating and cooling system of these hot batteries is designed well enough, the system is completely independent of the surrounding temperature.

5.4.2 General Aspects of Specification

The following aspects have to be taken into account when constructing a battery system:

- The energy content, which is correspondent to the height of the discharge current, has to be taken into account. The so called Peukert factor gives you an idea of the maximum energy that can be withdrawn from the battery. The smaller the Peukert factor, the better the battery. This is caused by the inner resistance of the battery and the slowness of the battery's chemistry.

In general:

$I^k \cdot t_e = C$, I is the discharge current, I^k is the simply calculated and by Peukert corrected discharge current, t_e is the discharge time, C is a constant, k is the so called Peukert factor may be typically between 1.1 and 1.5. In charts, the effective capacity H_x is shown as a function of the applied current I_x . The calculations can be done using the following equation [7]:

$$H_x = H_0 \cdot \left(\frac{H_0}{T_0 \cdot I_x} \right)^{k-1},$$

H_x is the wanted function value and the effectively available capacity [Ah] referring to Peukert's calculations.

H_0 is the manufacturer's capacity value [Ah] corresponding to the discharge time T_0 [h],

I_x is the available current (function variable) and

k is the Peukert variable

The energy content of a supercap can be calculated similarly to a capacitor: $W = \frac{1}{2} C U^2$. The influence of the inner resistance is taken into account using $R \cdot I^2$.

- Power requirements of the battery.
- Current exposure profile of the storage system: load profile (typical cycle), operating profile (development of the number cycles over a whole life span)
- The stress of a battery is standardized using the number of Ah in "C". 1C represents the charging current which is given by the rated capacity [Ah] of the battery.
- Cycle number balance of accumulators which refer not only to the application, but also to ageing phenomena
- Type, dimensions and weight
- Technology
- Temperature range
- Charging management (energy flow, balancing, supervision, MMI, etc.). In particular safety measures concerning overcharge, overdischarge, determination of the load level and the capacity, overtemperature and insufficient temperature protection.
- System integration: interaction between storages and the overall system using intelligence
- Modularisation: expandability, universality, simple integration, redundancy, combination of different systems and compactness are in this case the most important factors.
- System specific characteristics
- Price
- Environmental compatibility

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The spider diagram shows that the specification of batteries depends on many key parameters and can not only be defined by capacity or Cycles.

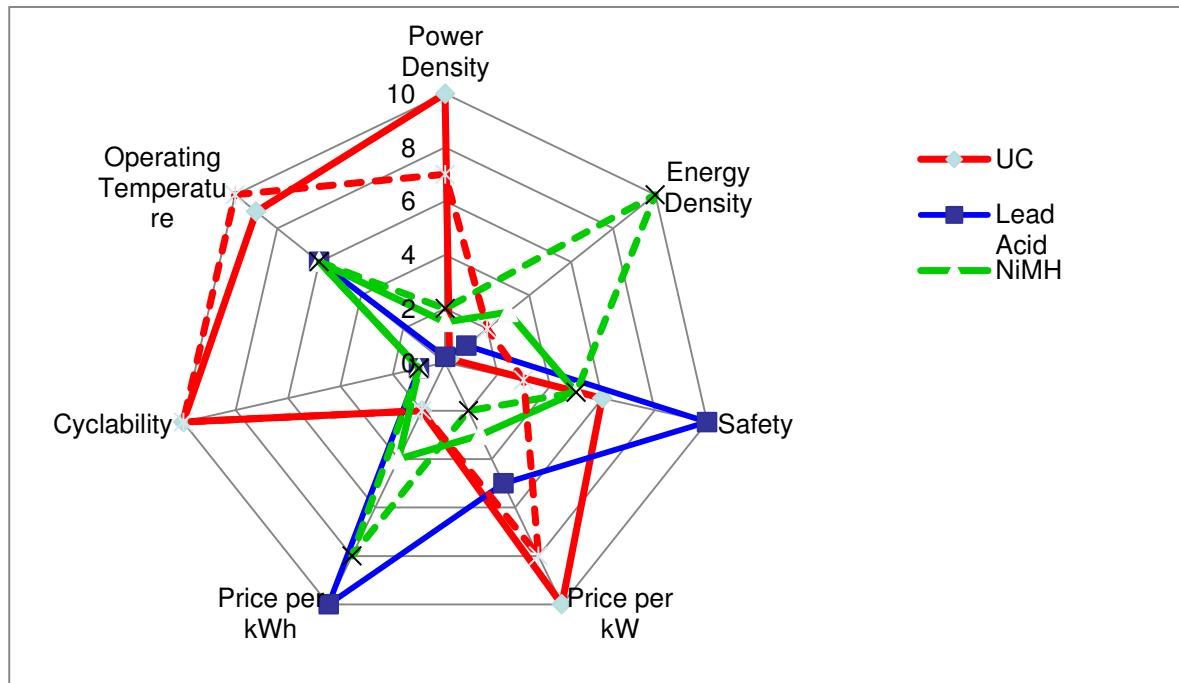


Figure: The spider diagram shows the many important specification criterias

5.4.3 Overview of Classical Charging Algorithms

Simple charging algorithms may only take the three variables voltage, current and temperature into account. Mathematically the following key informations are important:

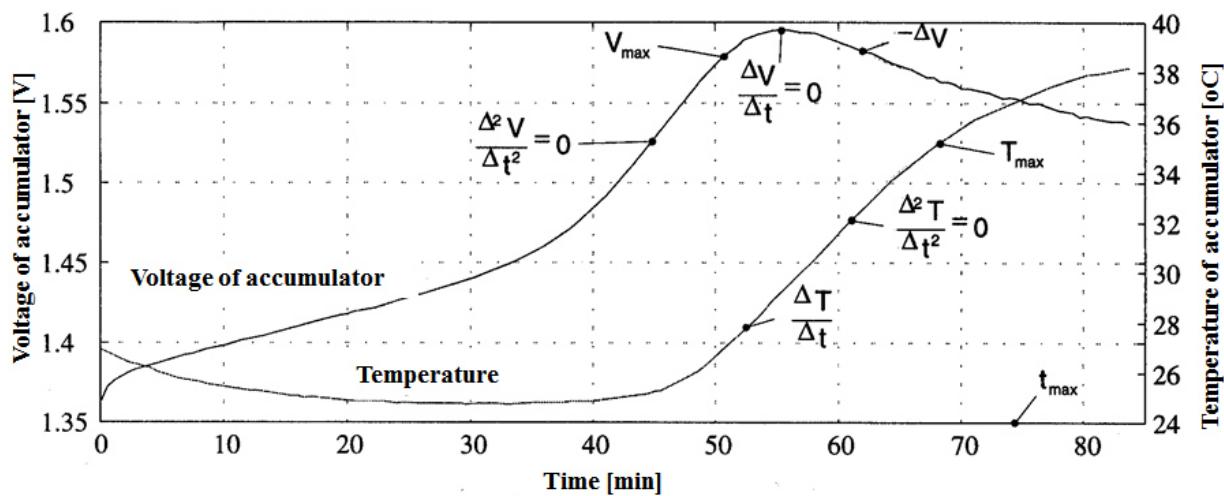


Figure: Important possibilities of charging effect recognition (Ref. Andreas Jossen [64])

In detail the criterias can be commented as follows:

Criteria	Detection	Comment
V_{max}	Reaching V max.	not reliable
$-\Delta V$	Voltage reduction (e.g.: NiCd: -30 mV/cell , NiMH: -10 mV/cell)	Often used. When warm, bad detection because of criteria.
$\frac{\Delta V}{\Delta t} = 0$	Derivate: detection of V max	Better, but difficult detection (no warming)
$\frac{\Delta^2 V}{\Delta t^2} = 0$	Reaching inflection point (then fully charged by minimal current)	For high currents. Current switched to a minimum when charged!
T_{max}	Over temperature	Not reliable!
$\frac{\Delta T}{\Delta t} = 0$	Derivate of temperature	a little bit better than T_{max}
$\frac{\Delta^2 T}{\Delta t^2} = 0$	Reaching inflection point of temperature	Inflection point has to be present; often over temperature curve!
t_{max}	Time criteria	Problem, if batteries are not empty. Only for 0.1C recommended

Table: different charging detection criterias

5.4.4 Simulation and Integration

For the integration of energy storage systems, the interaction of storages, intelligence and power electronics plays an essential role. Together with constructive circumstances, one can speak of integration.

The most important aspects in this case are the following:

- Simulation: Complex relationships and systems that refer to applications require simulations. Therefore, modelling energy storages and their surrounding area is essential. Supercaps are, in general, quite easy to simulate as the mathematical relations ($W = \frac{1}{2} CU^2$) are simple. In contrast, batteries contain many complex chemical reactions which makes the simulation a lot more difficult.
- Packaging: module connection (in series/ parallel), construction and a structure conforming to standards
- Balancing: compensation of all single cell voltages, cf. the supercap chapter
- Thermal management: cooling, automatic temperature control, sensor technology
- Safety: fuses, polyswitches, circuit breaker
- Monitoring of operating values

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5.5 Supercapacitors, Ultracapacitors, EDLC

5.5.1 Construction and Attributes

The storage principle

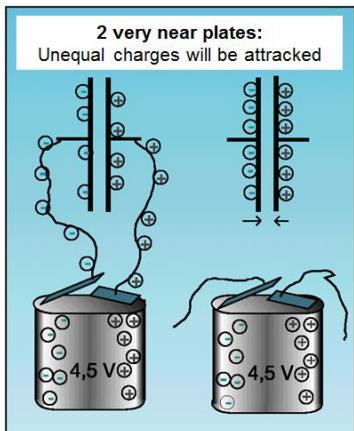


Figure: functional principle of a capacitor

Common lead acid batteries and other battery types use electrochemical reactions in order to store energy. In contrast, supercaps store energy only electrostatically. The basic principle is as simple as different electrical charges attract each other. Consequently, load carriers are transported to the capacitor's "planets" when a voltage is applied (lefthand figure) and stay there, even after separation (righthand figure). As a result, supercaps show the same characteristics as capacitors.

The ultracapacitor's secret is on one hand, that the surface is enhanced due to a great roughness and on the other hand, that thin insulation layers allow small distances between the layers.

Construction, models and characteristic values

This chapter gives you an overview of the characteristics of supercaps. Literature concerning technological aspects of supercaps and development trends within this topic can be found in the bibliography [15] to [35].

Definition of the double layer capacitor

An EDLC (Electrochemical Double Layer Capacitor) is a capacitor whose capacity is typically larger than 1 Farad and which can be charged very quickly. There are several different descriptions such as supercaps, ultracapacitors, boostcap or PowerCache, depending on the manufacturer. As already explained, the high capacity results on one hand from the large surface and on the other hand from the extremely thin dielectric. A SCAP typically consists of carbon electrodes, an aqueous or organic electrolyte and a separator:

Difference between "normal" capacitors and SCAPs is shown in the following figure:

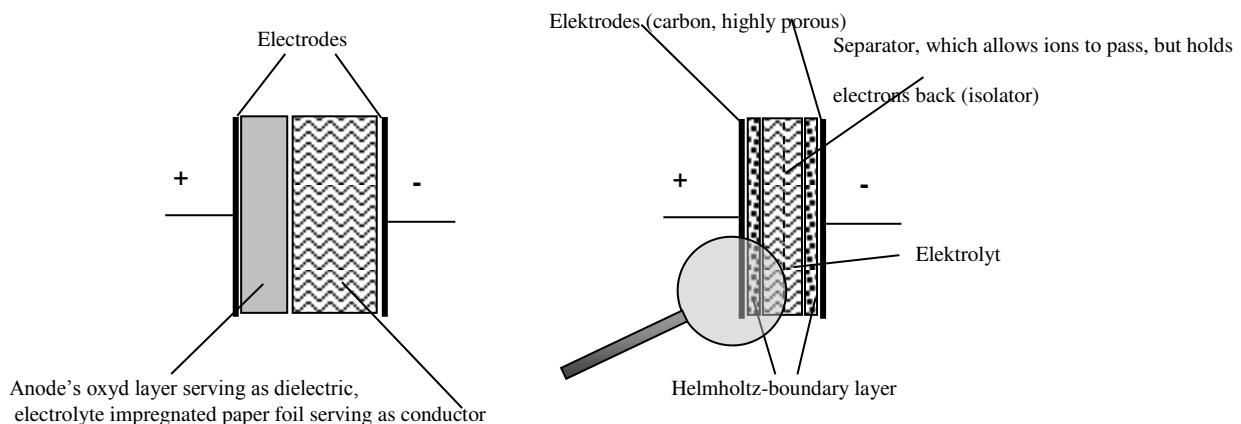
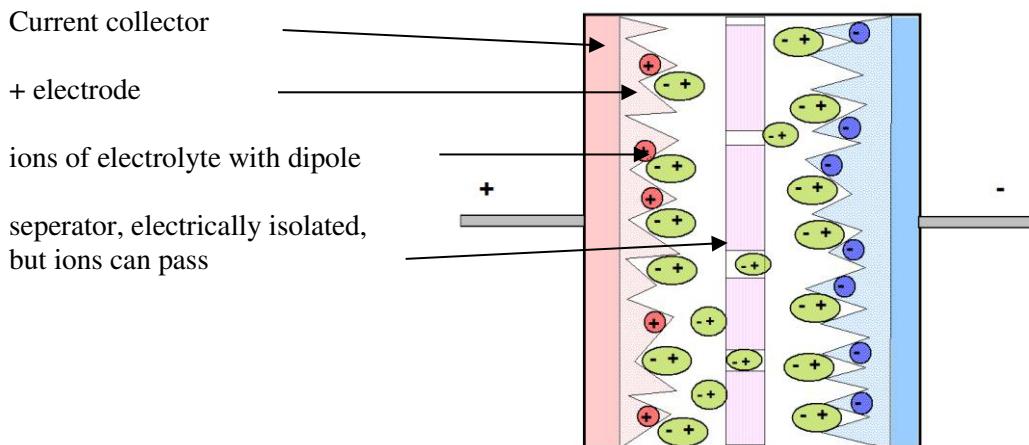
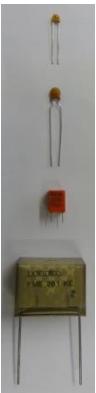


Figure: Difference between traditional electrolyte capacitors and SCAPs

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Because of symmetry there are two opposite loaded Helmholtz layers, which gives the SCAPs name "Electrochemical Double Layer Capacitor (EDLC)



	Capacity relations:	
	1	
	5	
	1000	
	500'000	and supercaps: 1'000'000'000'000'00

5.5.2 Design of Supercapacitor Storages

General aspects were already partly described within the battery chapter. Apart from that and besides the SCAP components' specific technology (containing the corresponding electrical models), the way of connection plays an essential role for the application. SCAPs wiring is necessary due to the following disadvantageous reasons:

- The SCAPs' voltage is very small (ca. 2V). Consequently, for different applications, several SCAPs have to be combined appropriately.
- Parameter spread exists (manufacturing differences, temperature, time depending parameter spread)
- Eventually, for this purpose, a load balancing has to be taken into account (charge-equalizing)
- In contrast to batteries, the SCAPs' voltage is not constant, but depends on the energy E and the capacity C using the square root:

$$U = \sqrt{\frac{2 \cdot E}{C}}$$

- As a consequence, the energy fluxes have to be regulated appropriately.
- An overvoltage protection is needed.
- Overvoltages or blackouts of single SCAPs need to be controlled, if necessary, using a „by-pass“ function.
- Polarity reversals while discharging towards zero have to be avoided.
- The construction should be designed for a long life span. The nominal voltage level has a great influence on the number of cycles! An operation at 2.5 instead of 2.7V can nearly double the number of cycles!
- System aspects: the SCAP-storage modularity has to be planned in detail. The energy management (intelligence) is directly connected to the overall system. One of the most important parts is the intelligent control and communication system, as it controls the energy fluxes, manages the charge distribution and not only observes monitoring exercises, but also the configuration and communication. The corresponding hardware has to be simple, space-saving and cheap. A standardized bus system (e.g. CAN) is mandatory in order to be able to integrate the storage into an existing application surrounding. [41] to [46] and [52], [53].
- SCAPs often appear in combination with batteries. Overall concepts can be found for example in the SAM concept (Super Accumulator Module) at Lucerne's University of Applied Sciences and Arts or in the concept of an ultrabattery (see figure in chapter 0) [47].

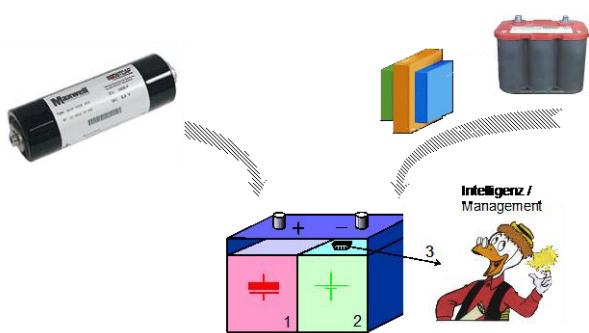


Figure: Simplified representation of the SAM concept of Lucerne's University of Applied Sciences and Arts

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5.5.3 Management System Design for SCAP-Modules without any Measures

Hereinafter, fundamental circuit variants of SCAPs which are able to fulfil the requirements of chapter 0 are shown. For each variant several advantages and disadvantages exist. The main disadvantage can be normally found at the cost expenditure in order to ideally fulfil the desired characteristics.

An overview of the different circuit variants are shown in the figure below:

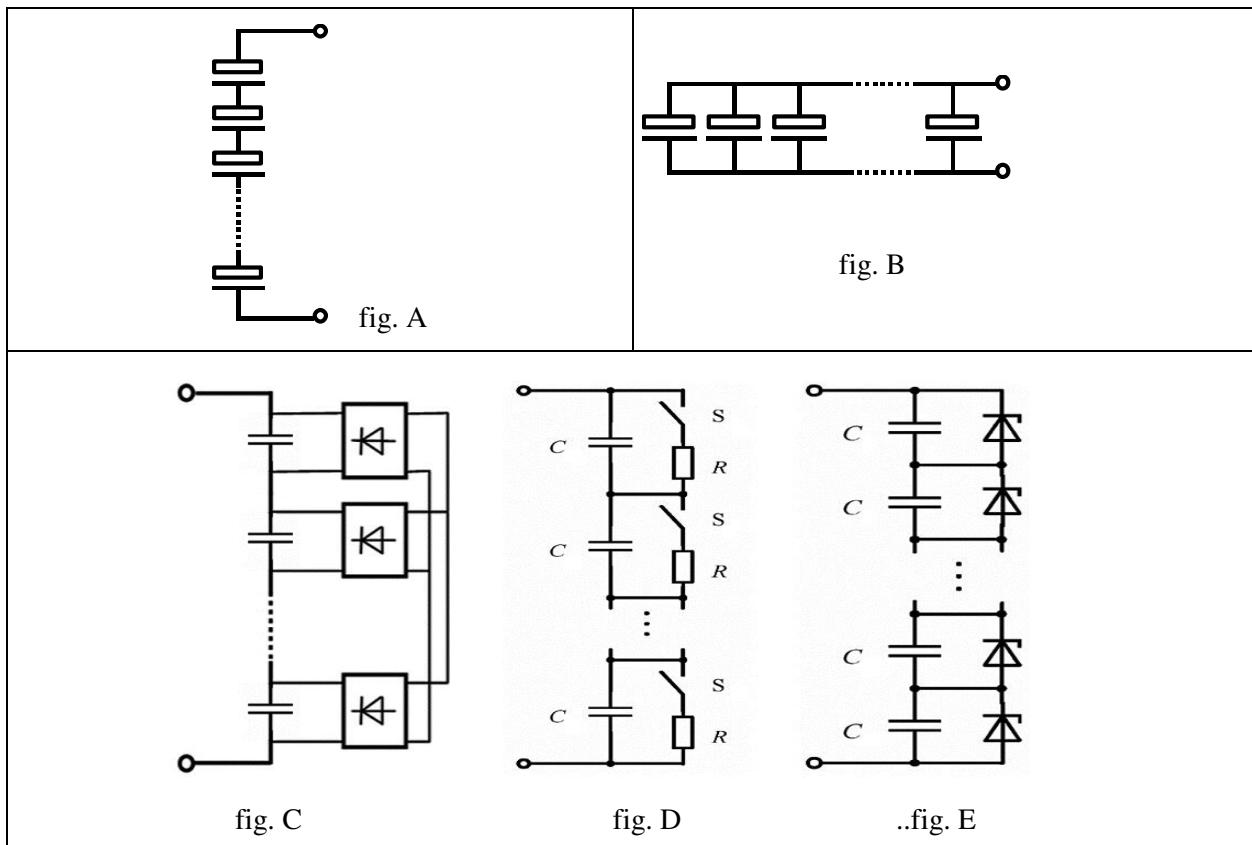


Figure: Different circuit variants for SCAPs

A: Serial connection

At first glance, the serial connection seems to be the best fit for a single SCAP or battery storage system when higher voltages are required. This circuit variant has a very high efficiency due to a small current at the same power level. But there are some severe disadvantages. If only one element fails and an interruption occurs, the whole stack is out of service and the customer can't use it anymore. In the case of a shortcut of a single element, the total voltage is distributed to $(n-1)$ elements which results in the danger of overvoltages (higher terminal voltage). SCAPs aren't able to tolerate overvoltages and therefore have to be monitored. Aggravating this situation, a spread of the inner resistances and capacities can be expected which can lead to a diverging of the terminal voltages. In order to avoid this problem, a charge equalization equipment or a voltage balancing can be used [48].

B: Parallel connection

For small operating voltages (\leq nominal voltage) or for huge current peaks, a parallel connection can be taken into consideration. These current peaks can appear both, while charging or discharging. Concerning parameter management, the parallel connection is completely problem-free [49]. In addition, compensating currents contribute to an homogenisation of the entire system.

In the case of a shortcut of a single element within a parallel connection, one has to pay attention that the other elements are not discharged and therefore uncontrollable currents occur.

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5.5.4 Management System Design for SCAP-Modules with Measures

In serial connections, all elements receive or contribute the same electrical charge. For a parameter spread, this can lead to overvoltages or even polarity reversal of the weakest element. It is mandatory to avoid such states. In the following part, different types of load leveling circuits are shortly explained which are also described in [49].

C: Virtual parallel circuit of Lucerne's University of Applied Sciences & Arts

The virtual parallel circuit switches SCAPs "so to speak" or simply "virtually" in parallel using a minimum of power electronics and an electrically isolated bypass. This configuration is responsible for the continuous charge equalization between the "weaker" and the "stronger" SCAPs [50]. The operation takes part without the use of intelligence and the circuit can be randomly cascaded. This compensation circuit can in principle work for SCAPs as well as for batteries.

D: Symmetry resistors (Wiring of resistors)

Resistors can be connected in series and over each single SCAP in order to reach load equalization. For the compensation process, the rise of losses is directly proportional to the compensation rate and to the smaller the resistances are. The resistances can be actively switched on or off depending on whether the SCAPs reached their maximum voltage or not.

As an example, one can show that the compensation process (all SCAPs have a voltage of 2.5V), when using four equivalent 10Ω resistances, lasts 12h. This holds if the four 800 Farad SCAPs (nominal voltage of 2.5V) have an asymmetric voltage spread of 2.8V, 2.4V, 2.2V, 2.6V and an assumed entire voltage of 10V with a maximum compensating current of 30mA. The generated steady current of 250mA causes continuous powerlosses of $P=10V \cdot 0.25A=2.5W$. If the compensation process has to be accelerated, the resistances have to be designed smaller. As a consequence the continuous power losses are dramatically increased. This circuit is recommended in [49]. According to this source, the balancing circuit is redundant, if the maximum entire voltage of a serial connection is smaller than $0.8*n*U_{Nenn}$.

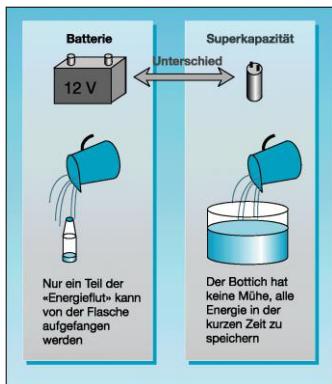
E: Zener diode circuit

This is a very cheap variant, which is unfortunately limited by the zener diode current. The load equalization takes only part, if the SCAPs are fully charged and the Z-diodes are conducting. Consequently, this circuit is in danger of Z-diodes failures!

5.6 Discussion: Batteries versus Supercaps

5.6.1 Batteries and Supercaps

The difference between batteries and supercaps mainly is, that batteries are able to store a lot of energy whereas supercaps can store less energy in a shorter period of time (few seconds). The figure on the lefthand side illustrates this characteristic using a water filling experiment with different water containers.



If batteries are nonetheless loaded with high power, huge losses have to be tolerated on one hand and on the other hand, the lifespan will be reduced: the maximum battery cycle number decreases quickly. Batteries have a better energy density, whereas SCAPs have a better power density. Taking the lifespan and the environmental impact into account, SCAPs receive a better result.

Figure: Storage characteristics of a battery in comparison to a SCAP

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5.6.2 Ragone Plot

The Ragone-plot diagram illustrates the two most important parameters for the differentiation of energy storage systems: the energy and the power density (see figure below). Using the SCAP parameter T (time constant = $R_s \cdot C$) for different foil types, lines can be plotted within the diagramm. These lines can be calculated as follows:

$$\text{In general: } E' = \frac{1}{2 \cdot m} C \cdot U_{scapmax}^2 \text{ and } P' = \frac{U_{scapmax}^2}{4 \cdot R_s \cdot m}$$

$$\text{For the diagram one receives: } \frac{E'}{P'} = \frac{4 \cdot R_s \cdot m \cdot C}{2 \cdot m} = 2T \text{ respectively } E' = 2T \cdot P' \text{ respectively } E' = \frac{T \cdot P'}{1800} \text{ for}$$

[Wh/kg] and [W/kg]!

Conventional capacitors have in fact a lot of power, but aren't able to store much energy. In contrast, batteries store a lot of energy, but experience difficulties with power peaks. Fuel cells are able to store a maximum of energy due to the fuel's enormous energy density.

SCAPs close the technological gap between those three storing technologies. They are able to cover huge power peaks and at the same time, they have a considerable energy content. New Li-ion batteries, which are optimized for power peaks, continuously compete with SCAPs.

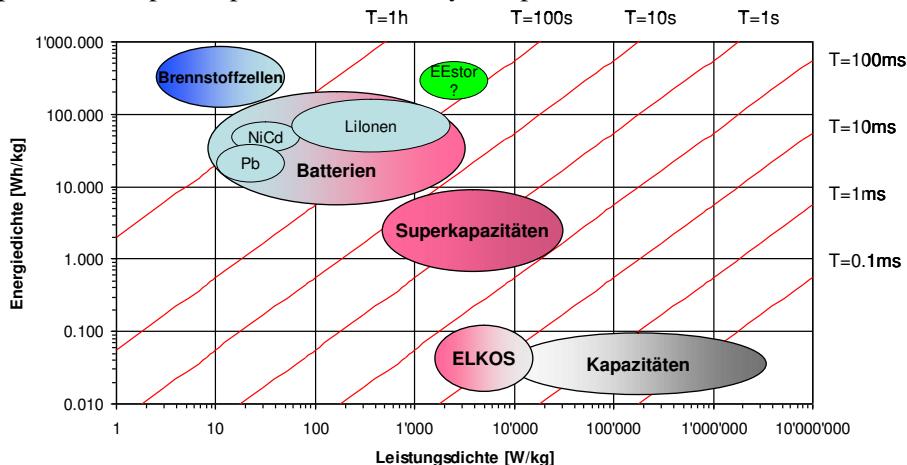


Figure: Application areas of energy storages within the Ragone-plot

5.6.3 Comparison by Table

The tabulated comparison of different values between batteries, SCAPs and conventional capacitors are shown as a general overview in the following figures:

	Batteries	EDLC (SCAP)	Conv. Capacitors
Time of Charge	1...5 h	0.3...30 sec	$10^{-3} \dots 10^{-6}$ sec
Time of Discharge	0.3 ... 20 h	0.3 ... 30 sec	$10^{-3} \dots 10^{-6}$ sec
Spec. Energy (Wh/kg)	10 ... 140	1 ... 10	< 0.1
Spec. Power (W/kg)	< 1000...2000	< 10000	< 100000
Lifetime (C/D cycles)	< 1500	> 500000	> 500 000
Efficiency	0.7 ... 0.90	0.85 ... 0.98	> 0.95

Figure: Characteristics of batteries and conventional capacitors in comparison to SCAPs

The following table contains a more detailed comparison of various batteries and SCAPs:

Storage system:	SCAP Maxwell	Blei Optima	NiCd	NaNiCl	Ni/MH	NaS	Li-Ionen LiCoO	Li-Ionen LiFePO
Energy density [Wh/kg]	5.5	31	50	110	80	107	140	80
Power density [W/kg]	<20'000	* 412	100	150	175	15	400	>1000
max. discharge rate	>>	10-15C	10C	gut	2C	C/8	5C	15C
Cycle number (lifespan)	1'000'000	250	1000	1000	1000	2500	800	2000
Self-discharge [% per month]	kaum	kaum	15	kaum **)	15	kaum **)	4	4
Recommended price per Wh in [Fr.]	15....25	0.25	0.6	0.7	0.5	0.6	0.5 4	

Figure: overview table of batteries in comparison to Maxwell SCAPs

**) unsuitable as traction battery!

For further comparisons between batteries and SCAPs, use the references shown in [50] to [61].

5.7 Learning Control

1. Which different kinds of batteries do you know? List advantages and disadvantages.
2. From the „energy storage“ point of view, what is so special about the construction and the application of SCAPs?
3. Why is it difficult to define the term “number of cycles”?
4. How can the strength of stress conforming to standards for energy storages be specified?
5. What is the Ragone-plot representing?
6. Which aspects have to be taken into consideration, if you want to integrate energy storages?
7. Which are the tasks of a BMS?
8. Which profiles are needed for the design of energy storages? Give a brief explanation!

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6. Energy Supply: Smart-Grids and Storages

6.1 Motivation, Typical Questions and Teaching Aims

6.1.1 Motivation and Typical Questions

In order to understand today's energy problems, the ability to control only single specific areas such as renewable energies, grids or e mobility is not sufficient. System correlations form the characteristic core questions today. The comprehension of this topic is shortly summarized in this chapter 6.

The question is, how the stability of the current power supply in connection with the continuous establishing of new renewable energies, is linked to infrastructure, storages, e-mobility and the need for supplying buildings with energy.

An additional goal of this chapter is to provide the knowledge of definitions, basic comprehensions and the vision of smart-grids. Theoretical inputs and exercises are designed to help understanding the challenges of the electric grid, especially peak-power handling. The interaction of components such as renewable energy sources, infrastructure, storages and management should become clearer. For this purpose, NEPLAN can be used profitably as a simulation tool. As a consequence, typical questions deal with future infrastructure developments and the interaction within grids and smart-grids in a liberalized electricity market as well as autonomy and efficiency of decentralized sub-grids.

6.1.2 Teaching Aims

1. Knowing the most important terms of energy supply and smart grids.
2. Knowing the opportunities and limitations of future energy supply.
3. Being able to do system analysis concerning decentralized storages.
4. Knowledge of simple regulation algorithms for decentralized grids.
5. Economic efficiency and market developments.
6. Battery storage measurements can be classified within the overall system.
7. Knowing the significance and the purpose of battery storage systems within the grid.
8. Comprehension of the components interactions.
9. Getting to know typical system correlations of a PV power station that is working in a system consisting of e-mobility, storage systems and the grid.
10. Optional: Knowing characteristic figures of consumers (electric vehicles) and decentralized feed-in (photovoltaic power plants) in the smart grid.
11. Optional: Being able to solve simple exercises using NEPLAN.

6.1.3 Important Terms

V2x: General term for all kinds of variations of the interaction between e-mobility, buildings and the grid

G2V: Grid to Vehicle is the most common unidirectional charging of EVs using the grid

V2G: Vehicle to Grid is the bidirectional energy exchange between the vehicle, battery and the grid

V2H: Vehicle to Home is equivalent to V2G, but the exchange takes place within the house, which communicates with the EVs, and not with the superior grid.

W2H: Work to Home is a definition of CC IIEE and is almost the same as V2G with the small difference, that the vehicle is loaded at the office during the day in order to use the noon PV power peak reasonably.

6.2 History and Definitions

- DER Distributed Energy Resources
- DG Distributed Generation (PV, wind, CHP (combined heat & power), others...)
- DR Demand Response → dynamic demand; loads according to the grid's needs
- DSM Demand Side Management → consumption steering using signals (offers of special tariffs)
- DSO Distribution System Operator
- EMS Energy Management System, as well as
- HEMS Home Energy Management System
- EPRI Electric Power Research Institute
- EV Electric Vehicle
- GT Gas turbine
- HVAC Heating, Ventilation and Air Conditioning
- IEA International Energy Agency
- IEEE Institute of Electrical and Electronics Engineering
- INAs Intelligent Network Agents
- ISO Independent System Operator: neutral coordinator of smart-grids
- PHEVs Plug-In Hybrid Electric Vehicles
- RES Renewable energy sources
- TES Thermal Energy Storage
- TOU Time of Use: tariffs according to the applied point of time (schedule)
- UPS Uninterruptable Power Supply
- VPP Virtual Power Plant

Smart-Metering means...

A smart meter is usually an electrical meter that records consumption of electric energy in intervals of an hour or less and communicates the collected information at least once a day back to the utility for monitoring and billing purposes. Smart meters enable a two-way communication between the meter and the central system. Unlike home energy monitors, smart meters can gather data for remote reporting (Wiki).

→ e.g. Italy: Enel S.p.A. (Ente Nazionale per l'Energia elettrica) meters are fully electronic and smart, with integrated bi-directional communications, advanced power measurement and management capabilities, an integrated, software-controllable disconnect switch. Between 2000 and 2005 Enel deployed smart meters to its entire 27 million customer base. Wireless communication planned.

→ Projects: Already all over the world: Japan, USA, Canada, UK, NZ, NL, Spain, France,

Smart-Grid means...

Smart grid is a type of electrical grid which attempts to predict an intelligent response to the behavior and actions of all electric power users connected to it - suppliers, consumers and those that do both – in order to efficiently deliver reliable, economic, and sustainable electricity services (Wiki).

→ The first and still the largest example is the Italian system installed by Enel, 2005. The Telegestore project was highly unusual in the utility world because the company designed and manufactured the meters in-house. First commercial scale use of smart grid technology to the home, and delivers annual savings of 500 million euro at a project cost of 2.1 billion euro.

In the US, the city of Austin, Texas has been working on its smart grid since 2003, with smart meters that communicate via wireless mesh network. It currently manages 200,000 devices in real-time.

Boulder, Colorado completed the first phase of its smart grid project in August 2008. Both systems use the smart meter as a gateway to the home automation network (HAN) that controls smart sockets and devices. Hydro One, in Ontario, Canada is in the midst of a large-scale Smart Grid initiative, deploying a standards-compliant communications infrastructure. By the end of 2010, the system will serve 1.3 million customers in the province of Ontario. The City of Mannheim in Germany is using realtime Broadband Powerline (BPL) communications in its Model City Mannheim "MoMa" project.

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6.3 Smart-Grid Attributes Today and in Future

1. Reliability of power supply.
2. Cost optimization of basic supply, decentralized production and storages
3. Negligible environmental impacts
4. Reduce consumption and enhance efficiency
5. Flexibility and redundancy of the grid
6. Grid quality
7. Tracking of critical components

And in future:

8. Real time visualization
9. Infrastructure: increase capacity, even n-1 or higher
10. Prevent bottlenecks using dynamic control
11. Additional benefits: from being a consumer to being a prosumer = producer + consumer

6.4 Smart-Grid Goals

1. Successful interaction of µgrids
2. Optimization of the total energy flow (peaks, @better times, costs...)
3. Efficiency, especially by
4. More transparency (smart meter)
5. Liberalized and extended market: dynamic tariffs, agents, DR, DSM
6. Reaching stability due to increased interventions

6.5 Topics within Decentralized Grids

1. Production: more unpredictable power peaks (wind, PV, ...)
2. More peaks caused by fast charging.
3. Bottleneck management.
4. System services.
5. New “services“.
6. Knowledge about what is currently going on (smart metering). This results in a change in behavior as the need of energy is known.
7. Adaptive control: anticipate peaks...
8. Grid reinforcement and application of storage systems (from infrastructure to V2G)
9. Telecommunication: information exchange.
10. Intelligence in order to cope with complexity.
11. Spreading, e.g. by using the open-source concept

6.6 Storages in Decentralized Grids

Different issues, such as private or public transportation, electrical grids, microgrids, energy storages and e-mobility, are all tightly linked to each other. In future developments these facts have to be taken into account. The connection “grid-living-mobility” is shown in the following figure:

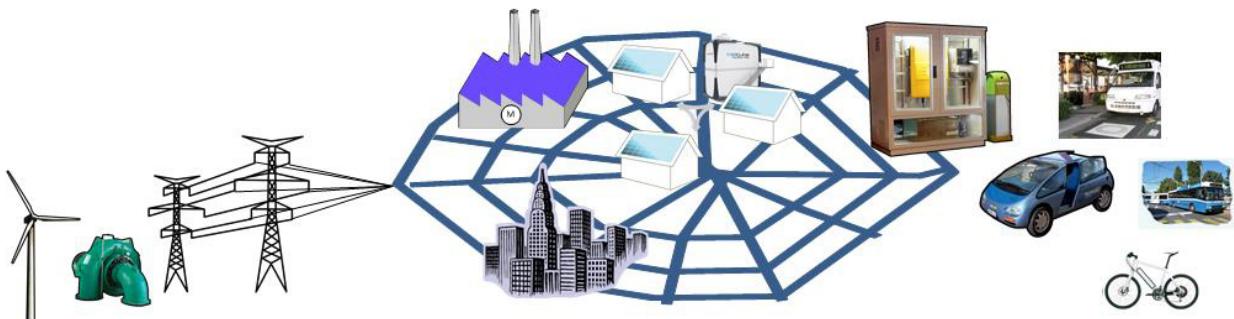


Figure: The understanding of the “Grid-Living & Mobility” claim

Renewable energies are most recently extremely popular. Especially the number of wind and photovoltaic power plants is growing rapidly. The EU's ambitious goal to cover 20% of the overall energy consumption using renewable energy sources until 2020, which was declared in March 2007, is contributing to this trend. For energy suppliers, decentralized power stations are more difficult to manage, as the energy production suffers from great fluctuations.

For energy suppliers, it is important to buffer great power fluctuations not only by using decentralized power stations (such as photovoltaic or wind power plants), but also by using consumers as a buffer. If this isn't possible, the distribution networks need to be oversized, so that none of the possible extreme situations leads to a line overload. From an economic point of view, this behavior is senseless.

Decentralized, by the energy supplier controlled storages can be used for peak shaving. In Switzerland, pump storage power plants are often used for peak shaving, although they fit only a limited amount of extreme situations as they are centrally located and the regulation speed can only be adapted partly to the requirements of photovoltaic and wind energy power plants.

Lately, plug-in hybrids as well as pure electric vehicles are not only for energy suppliers (especially in the US and Japan), but also for the automotive industry (e.g. Toyota 1/X, Honda CR-Z, GM E-Flex, Mitsubishi i-MiEV, VW up!) at the center of discussion.

Scenarios of the Swiss Federal Office of Energy (BFE) concerning the ability to reach Kyoto aims show that it is much more difficult to fulfill the fuel goals than the combustible targets. Neither plug-in hybrids (PHEV) nor e-mobiles are an option to reduce CO₂ emissions within the mobility sector. The effect of the replacement of fossil fuels by electricity is especially in Switzerland significant as the Swiss electricity mix is almost CO₂ neutral.

At the latest automobile exhibitions (IAA, Frankfurt, Tokyo Motor Show), car manufacturers attracted attention by continuously new announcements of concepts that contain a more or less big electrical energy storage system. The VW up!, which was shown already at the IAA 2007 in Frankfurt, serves as an example. General Motors recognized the trend and currently plans a whole new series, called “E-Flex”, based on the PHEV concept. For this purpose, huge development orders have been given to different battery companies. Toyota's concept is to enable efficient mobility using extreme lightweight constructions. The car is designed as PHEV.

6.7 Smart-Grid Mechanisms

In production (e.g. PV), peaks can be shaved directly at the source using storages. In addition, storages are able to balance load peaks as well.

If supply and demand are in mismatch, demand respond (DR) can be used to control supply due to tariff variations:

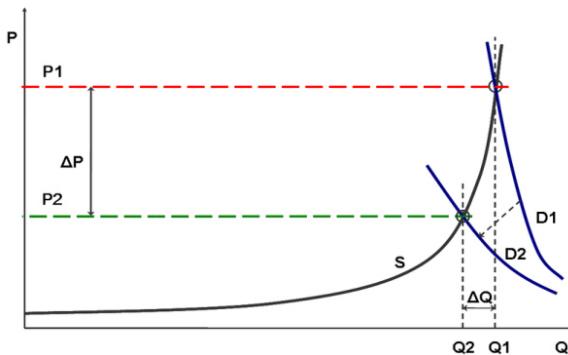


Figure: The typical demand-respond graph

The price (P)/ needed quantity (Q) curve of supply (S) is set in comparison to the demanded power (D1, D2). Without the opportunity to cover bottlenecks, a much higher price is being paid (D1) if there is a lack of available energy. If it's possible to partly cover the gap of missing energy (e.g. by using storages), delta Q less energy is needed and therefore the price drops dramatically (D2). It was shown, that a reduction of delta Q of only 5% causes a current price reduction of 50%!

- Selective load switching with the aim to balance supply and demand is known as DSM (Demand Side Management).
- Transferring loads to other times is called load shifting, while load shedding (load drop) is an even more drastically intervention. Both of them can take place automatically.

6.8 V2x: Significance of Mobile and Stationary Storage Interactions

V2G (Vehicle to Grid) was just recently characterized as a new term in relation to decentralized energy supply and decentralized energy storage in residential buildings. It explicitly claims for the application of the vehicle's energy storage within the living area. The aim is not only to give opportunities to the energy supplier for the improvement of grid stability, but also to supply residential buildings in isolated operation during black outs.

As a consequence of V2G, charging points and vehicles have to be connected bidirectional. V2G is rather a long term vision and a hypothesis for various equivalent ideas to synchronize different components reasonably. W2H (work to home) is a CC IIEE concept and contains the idea to charge the e-mobile at work during the day instead of charging it at home in the evening or during the night.

The problem of energy buffering becomes more and more important, especially for many decentralized energy producers who use alternative energy sources. The mix, the type of the energy storage system as well as its availability is playing an essential role in this context. The combination (aggregation) of spread energy storages and their interaction from a general point of view of thermal and electrical energies within the whole system are interesting as well.

A possible development of V2x technologies is shown in the following diagram **Fehler! Verweisquelle konnte nicht gefunden werden.**:

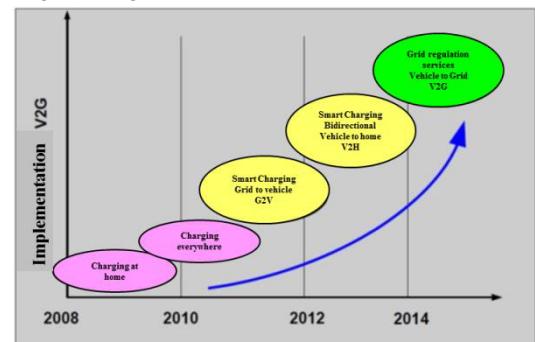


Figure: Th V2x technologies migratio steps (R. Horbaty, [15])

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Development steps, applied technology	Time horizon	Contents and research fields	Participants	(Industrial) products in CH
Charging at home at off-peak times (e.g. controlled via time switches)				
Electric mobiles, electric vehicles with two wheels	Today	Batteries Grid load and grid capacity Basics of the energy economy (life cycle assessment, electricity market)	Energy suppliers Battery manufacturers	Chargers External power outlets 10A, 240V, single-phase Development of new business segments for energy suppliers
Purchase of green energy for charging (annual balance)	Today	Research programs Renewable Energies	Energy suppliers Vehicle owners	Own facilities Facilities of a third party, energy suppliers
Plug-In Hybrid Electric Vehicles (PHEV) Battery capacity 10kWh	As of 2010	Batteries Intelligent vehicle load management	Automobile manufacturers Battery manufacturers	External power outlets 16A, 240V, three phase Power electronics for vehicles
Charging everywhere (workplace, shopping center, parking deck)				
Charging point including data collection and billing possibilities	As of 2012	Grid load and grid capacity: Consequences for batteries and grids of fast charging	Energy suppliers Communities Major distributor Fleet operators (e.g. post)	Extension of electrical building installations Charging points even for fast charging, 400V and max. 40A Data collection devices/billing systems, e.g. credit cards etc.
Smart Charging - one way, ("grid to vehicle", G2V)				
Implementation of smart meters, grid optimized charging (grid load, electricity prices, etc.)	2010	Batteries Grid regulation Energy suppliers	Meter manufacturers Manufacturers of electronic devices Software companies	Intelligent current measurement devices Automated billing systems, billing via internet Further development of business segments for energy suppliers
PURE green energy: Charging ONLY with green energy Charging current from defined electricity sources	2010	Research programs Renewable energies EEC Grids	Telecommunication provider Energy suppliers	SMS communication
Smart Charging - bidirectional, ("vehicle to home", V2H)				
Return of stored energy back to the grid Peak load management	2012	Batteries Grid regulation	Energy suppliers Meter manufacturers	Two-way chargers Converters within a vehicle
Grid regulation services, "vehicle to grid" (V2G)				
Power provision for primary regulation, provision of balancing power	2014	Development of a complete "vehicle to grid" concept (V2G)	Swissgrid Energy suppliers	Intelligent communication structures Energy suppliers/ vehicles

Figure: Development steps of V2x technologies [15]

6.9 Project-References about Smart-Grids (2012)

- Example of action plan UK SuperGen: WP1: Reliability and security (whole system), WP2: decentralized operation and control, WP3: DSM (Demand Side Management), WP4: Microgrids, WP5: Foresight, WP6: System Evolution, WP7: Outreach
→ www.supergen-networks.org.uk
- EPRI: Electric Power Research Institute (California, USA),
→ www.epri.com
→ IntelliGrid, www.epri-intelligrid.com
- Capgemini (worldwide reunion): → www.capgemini.com/energy
- IBM, institute for business value: → www.ibm.com/iibv
- USA DOE (dep. of energy): The modern grid strategy:
→ www.netl.doe.gov
- GridWise Alliance, Washington DC: → www.gridwise.org
- General Electric: → www.gepower.com
- «Distribution Vision 2010» → look @ IEEE
- Galvin initiative: www.galvinpower.org
- EDF (France) «Power-Strada», IEEE → www.ieee-pes.org (2010)
- European Union Smart Grid: → www.smartgrids.eu
- Newsletter SmartGrid, e.g. → <http://www.smartgridnews.com>

6.10 Grid Simulations

The structure of the grid would be changed fundamentally if the current grid is reconstructed as smart grid. Energy production takes place more and more decentralized and energy flows are bidirectional. New decentralized power stations (in particular photovoltaic power stations) have to meet voltage limitations at the feed-in point. The capacity of the operating material is calculated by load flow calculations of the bidirectional grid. Furthermore, an optimization of the energy flows reduces grid losses. All calculations are made by using grid calculation simulation programs such as NEPLAN or DigSilent.

6.11 Learning Control

1. What is a smart grid?
2. What's new about smart grids and which current questions have already been discussed previously?
What are the main drivers of the smart grid?
3. Which challenges appear while attempting to manage the system of energy supply of buildings, new renewable energies, storage systems, feeding lines, e-mobility and grids?
4. What does “peak shifting“ mean?
5. Which electrical power supply challenges exist today?
6. What's the purpose of a grid simulation software such as NEPLAN? What's the advantages of NEPLAN compared to MATLAB?
7. What does V2G stand for and what does it represent?
8. Name advantages and disadvantages of V2G and V2H?
9. Explain characteristic correlations of the “grid-living-mobility” system.
10. Which role are e-mobile batteries being able to play within the overall system of buildings and grids?

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Chapter 7

Appendix 1: Additional Thermodynamic Aspects

7.1 Energy Balance Equation for an Open System (1^{st} Law of Thermodynamics)

The energy balance for an open system can be written as:

$$\frac{dE}{dt} = \sum \dot{Q} + \sum P + \sum_{in} \dot{m}_{in} \left(h + \frac{c^2}{2} + g z \right)_{in} - \sum_{out} \dot{m}_{out} \left(h + \frac{c^2}{2} + g z \right)_{out}. \quad (7.1)$$

The right hand side of this equation denotes the change in the energy content of the system. On the right hand side of the equation there are the sum of the net heat flow rates ($\sum \dot{Q}$), the sum of the net power inputs ($\sum P$) and the sum of the energy fluxes through the inlets and the outlets.

For **steady-state processes**, the changes over time are equal to zero ($d/dt = 0$). In technical applications, machines and equipment frequently operate at steady state.

For the frequently occurring special case where only one fluid flows through the control volume at steady-state, i.e. $\dot{m}_e = \dot{m}_a = \dot{m}$, the power balance equation is:

$$\sum \dot{Q} + \sum P = \dot{m} \left[\left(h + \frac{c^2}{2} + g z \right)_{out} - \left(h + \frac{c^2}{2} + g z \right)_{in} \right] \quad (7.2)$$

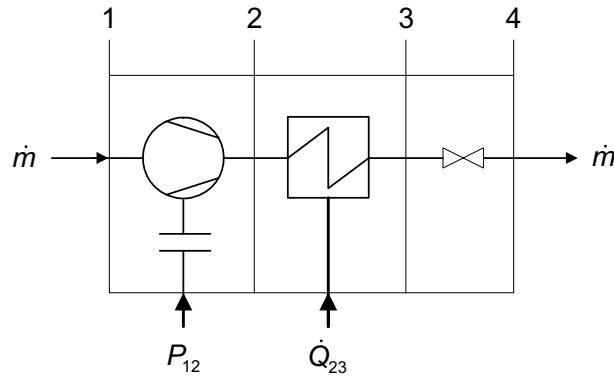
When applying the power balance to a fluid flow which flows through several control volumes one after the other, we identify the flow cross-sections (states) on the boundaries of the control volumes using numbers 1, 2, 3,

The power balance equation for the first control volume (1 → 2) is then:

$$\dot{Q}_{12} + P_{12} = \dot{m} \left[h_2 - h_1 + \frac{1}{2} (c_2^2 - c_1^2) + g (z_2 - z_1) \right] \quad [W] \quad (7.3)$$

By dividing by the mass flux \dot{m} :

$$q_{12} + w_{t12} = h_2 - h_1 + \frac{1}{2} (c_2^2 - c_1^2) + g (z_2 - z_1) \quad [J/kg] \quad (7.4)$$



This equation only contains specific energies. The quotients are called:

$$q_{12} = \frac{\dot{Q}_{12}}{\dot{m}} = \text{specific heat}$$

$$w_{t12} = \frac{P}{\dot{m}} = \text{specific technical work}$$

This energy balance equation is of great importance: It connects the energy transported across the system boundary in the form of heat and work to the change in the state of the fluid (enthalpy, kinetic and potential energy). It applies for every steady-state process, including irreversible processes.

7.2 Entropy and the 2nd Law of Thermodynamics

The 1st LT is the energy conservation law, i.e. it provides information on the quantity of energy. It does not say anything about the quality. The 2nd LT is the "**mistress of natural events**", because it "**rules on**" what is allowed and what is not allowed. The 2nd LT is an empirical fact (as is the 1st LT).

The 1st LT states: There are different forms of energy, they are conserved during energy conversions (energy balance).

The 2nd LT states: Heat can only partially be converted into work.

We introduce the entropy S for quantitative formulation of the 2nd LT by using the following postulates:

1. Every system has an extensive state variable called entropy S .
2. The entropy S of a system changes
 - through heat being transferred across the SB: dS_Q
 - through material being transported across the SB: $\dot{m}s$
 - through irreversible processes inside the system: dS_{irr}
3. The entropy transferred with heat dQ across the system boundary is

$$dS_Q = \frac{dQ}{T} \quad (7.5)$$

whereby T is the thermodynamic temperature at the place on the system boundary at which dQ is transferred. The thermodynamic temperature is a universal, not negative temperature (T in Kelvin).

4. The entropy created by irreversible processes inside the system is never negative; it is zero for reversible processes.

$$dS_{irr} \geqq 0 \quad (7.6)$$

Explanations:

Entropy has the unit

$$dS_Q = \frac{dQ}{T} \quad [\text{J/K}]$$

Entropy is an extensive state variable. The *specific entropy* is

$$s = \frac{S}{m} \quad [\text{J/kgK}]$$

The entropy transported (= entropy flow) with a mass flow \dot{m} is

$$\dot{S} = \dot{m}s \quad [\text{W/K}].$$

The statements of the 2nd LT on the change in entropy allow an entropy balance equation to be written for every process in a closed system (open systems follow later):

$$dS = dS_Q + dS_{irr} \quad (7.7)$$

Heat dQ and entropy dS_Q transferred by heat are linked by a state variable, namely the thermodynamic temperature:

$$dQ = TdS_Q, \quad dq = Tds_Q$$

The thermodynamic temperature is zero at the lowest possible temperature and is measured in Kelvin.

$$dS_Q = \frac{dQ}{T}, \quad \text{always } T > 0$$

I.e. T never becomes negative.

7.3 Exergy and Anergy

The 1st law of thermodynamics tells us that energy always remains constant in a closed system. Since every open system can be transformed into a closed system by adding the environment, it is always possible to create a system where no energy can be produced or destroyed. Therefore a loss of energy is not possible, as through a thermodynamic process energy can only be converted from one form to another. Possible forms of energy are:

- mechanical energy,
 - kinetic energy
 - potential energy
- electrical energy and
- thermal energy
 - heat
 - enthalpy
 - internal energy

Mechanical and electrical energy are the two forms of energy that can be converted completely into every other form of energy. However, the conversion of thermal energy into other forms is limited by the 2nd law of thermodynamics. For example, it is not possible to use the large amount of energy stored in the environment, which shows that the state of the environment influences the convertibility of thermal energy in a system. Thus thermal energy consists of two different parts of energy: Exergy, which can be completely converted into any other form of energy and anergy, which cannot be converted into another form.

- **Exergy:** Energy with unlimited changeability (mechanical, electrical, potential, kinetic energy)
- **Anergy:** Energy with no changeability (internal energy of the environment)
- **Exergy + Anergy:** Energy with limited changeability (thermal energy)

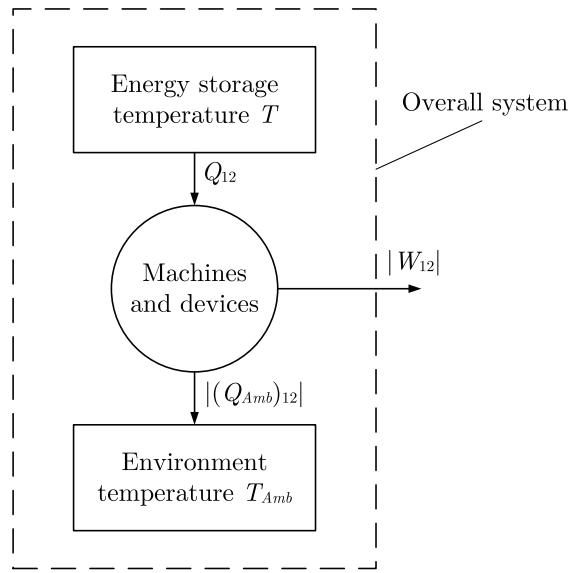


Figure 7.1: Transformation from heat to work [Stephan, 1992]

Every form of energy consist of exergy and anergy, although one of the two parts can be equal to zero. It can be written:

$$\text{Energy} = \text{Exergy} + \text{Anergy} \quad (7.8)$$

The 1st law of thermodynamics can be formulated as:

In all processes the sum of exergy and anergy remains constant.

The messages of the 2nd law of thermodynamics are:

1. **In all irreversible processes exergy is converted into anergy.**
2. **The exergy only remains constant in reversible processes.**
3. **It is impossible to convert anergy into exergy.**

7.3.1 Exergy and Anergy of Heat

An engine (for example a cylinder in a piston engine) is supplied with energy in the form of heat at a temperature T and it should be investigated to which extend the total heat energy can be converted into technical work. In other

words, the exergy of the heat should be calculated. To get a maximum of technical work, all thermodynamic processes need to be reversible. Thus, to fulfill the 2nd law of thermodynamics ($dS \geq 0$), one part of the supplied heat needs to be transferred to the environment. For the adiabatic system (see figure 7.1) the 2nd law of thermodynamics can be written as:

$$-\Delta S_{12} + \Delta(S_{Amb})_{12} + \Delta S_{irr} \geq 0 \quad (7.9a)$$

$$-\int_1^2 \frac{dQ}{T} + \int_1^2 \frac{|dQ_{Amb}|}{T_{Amb}} + \int_1^2 dS_{irr} \geq 0 \quad (7.9b)$$

dS_{irr} is the entropy change of the engine. According to the requirements (all processes are reversible), the engine gets back to its initial state after the end of the processes. Therefore $\int_1^2 dS_{irr} = 0$ and equation 7.9b is then

$$-\int_1^2 \frac{dQ}{T} + \int_1^2 \frac{|dQ_{Amb}|}{T_{Amb}} = 0 \quad (7.10)$$

The 1st law of thermodynamics for the engine can be written as

$$Q_{12} = |(Q_{Amb})_{12}| + |\Xi_{12}|, \quad (7.11a)$$

or in differential form

$$dQ + dQ_{Amb} + d\Xi = 0. \quad (7.11b)$$

After inserting equation 7.11b into equation 7.10 we obtain the exergy of the heat that enters the engine

$$-\Xi_Q = \int_1^2 \left(1 - \frac{T_{Amb}}{T}\right) dQ \quad (7.12)$$

or in differential writing

$$-\Xi_Q = \left(1 - \frac{T_{Amb}}{T}\right) dQ. \quad (7.13)$$

The anergy of the heat that enters the engine can be written as

$$d\Lambda_Q = T_{Amb} \frac{dQ}{T} \quad (7.14)$$

7.3.2 Exergy and Anergy of a closed system

A closed system expands and carries out useful work:

$$W_{V1Amb,rev} = - \int_1^{Amb} (p - p_{Amb}) dV = - \int_1^{Amb} pdV - p_{Amb}(V_{Amb} - V_1) \quad (7.15)$$

The integral can be replaced with the balance equation of the 1st law of thermodynamics:

$$U_{Amb} - U_1 = Q_{1Amb} - \int_1^{Amb} pdV. \quad (7.16)$$

This results in:

$$-(W_V)_{1Amb,rev} = -(U_{Amb} - U_1) + Q_{1Amb} - p_{Amb}(V_{Amb} - V_1) \quad (7.17)$$

The exergy of a closed system is the achievable maximum value of the useful work released when the state of the system is changed from state 1 to the state of the environment. The process must be reversible. Since only the exergy of the internal energy is to be determined, heat passes the system boundary only as anergy. The heat can then be written as

$$Q_{1Amb} = T_{Amb}(S_{Amb} - S_1) \quad (7.18)$$

By inserting equation 7.18 into equation 7.17 we get the exergy as maximum useful work of a closed system

$$\Xi_{Amb} = -(W_U)_{1Amb,max} = U - U_{Amb} + p_{Amb}(V - V_{Amb}) - T_{Amb}(S - S_{Amb}) \quad (7.19)$$

The anergy Λ_{Amb} is the difference of the internal energy U and the exergy Ξ_{Amb}

$$\Lambda_{Amb} = U - \Xi_{Amb} = U_{Amb} - p_{Amb}(V - V_{Amb}) + T_{Amb}(S - S_{Amb}) \quad (7.20)$$

7.3.3 Exergy and Anergy of an open system (without derivation)

Exergy of a flowing fluid:

$$\dot{\Xi}_H = \dot{m} \left[(h - h_{Amb}) + \frac{1}{2}c^2 + gz + T_{Amb}(s_{Amb} - s) \right] \quad (7.21)$$

Anergy of a flowing fluid:

$$\dot{\Lambda}_H = \dot{m} \left[h_{Amb} + T_{Amb}(s - s_{Amb}) \right] \quad (7.22)$$

For a ideal gas:

$$\dot{\Xi}_H = \dot{m} \left[c_p(T - T_{Amb}) - T_{Amb} \left(c_p \ln \frac{T}{T_{Amb}} - R_i \ln \frac{p}{p_{Amb}} \right) \right] \quad (7.23)$$

For fluids (incompressible):

$$\dot{\Xi}_H = \dot{m} \left[c_p \left(T - T_{Amb} - T_{Amb} \ln \frac{T}{T_{Amb}} \right) + v(p - p_{Amb}) \right] \quad (7.24)$$

7.4 Heat Transfer

Basically, heat can be transferred in two ways, through contact and through radiation. In the case of contact, a distinction is made between transfer through a conductor and through convection. Therefore a distinction is made between the three different heat transfer mechanisms: heat conduction, convection and radiation.

7.4.1 Heat Conduction

This takes place within all materials if there is a temperature difference. According to Fourier's law the heat flux is proportional to the negative temperature gradient times the thermal conductivity (λ):

$$\dot{q} = -\lambda \frac{dT}{dx} \quad (7.25)$$

Based on the energy balance for an infinitely small control volume a differential equation for the temperature can be derived:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c_p} \frac{\partial^2 T}{\partial x^2} \quad (7.26)$$

7.4.2 Heat Convection

In a flowing fluid, besides thermal conduction, energy is also transported due to the macroscopic motion of the fluid. If we imagine a surface which is located in the fluid at a fixed position heat is transported through the surface along the temperature gradient and by enthalpy and kinetic energy transport due to the fluid motion. This superimposition of conduction and energy transport through the flowing fluid is referred to as convective heat transfer.

Based on the causes of fluid flow, a distinction is made between:

- *forced convection*, if the flow e.g. has been artificially forced by a pump or a ventilator.

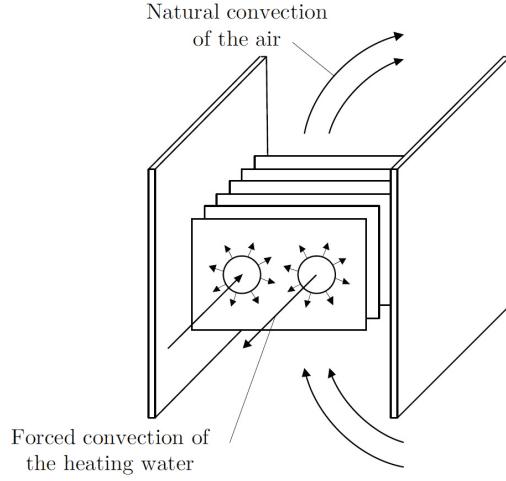


Figure 7.2: The two kinds of convection, illustrated for a space heater

- *free convection*, if the flow has been caused by density differences.

The heat flux at a wall \dot{q}_W depends on the temperature and the velocity field in a very complex way, which makes the calculation rather difficult. Therefore a new quantity, the heat transfer coefficient, is defined:

$$\alpha := \frac{\dot{q}_W}{\vartheta_W - \vartheta_F} \quad (7.27)$$

The heat flux is then given by

$$d\dot{Q}_W = \alpha(\vartheta_W - \vartheta_F)dA \quad (7.28)$$

$$\dot{q}_w = \frac{d\dot{Q}_W}{dA} = \alpha(\vartheta_W - \vartheta_F) \quad (7.29)$$

Influencing factors on the heat transfer coefficient are:

- Forced convection

$$\alpha = \alpha(\nu, c, L_{char}, \rho, c_p, \lambda, \dots)$$

- Free convection

$$\alpha = \alpha(\Delta T, \rho, c_p, \lambda, \dots)$$

Many factors affect heat transfer. It is not possible to describe every model experimentally or analytically. For this reason, findings regarding an object are transferred to objects which are physically similar. *E. W. Nusselt (1882-1957)* converted differential equations so that dimensionless variables appear which unite several parameters and make the problem clearer. These variables are the same for similar problems. The calculation of the heat transfer coefficient using the Nusselt relationship is treated in the script [The,].

7.4.3 Thermal Radiation

Every body with a temperature above 0 K emits thermal radiation, (electromagnetic radiation). The *Law of Stefan Boltzmann* describes the physical correlation:

$$\dot{q} = \varepsilon \sigma_S T^4 \quad (7.30)$$

σ_S is the Stefan-Boltzmann constant and ε is the emissivity. They are defined as

$$\sigma_S = (5,670373 \pm 0,000021) \cdot 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4} \quad (7.31)$$

$$\varepsilon = \frac{\text{emitted radiation}}{\text{emitted radiation of a black body}} \quad (7.32)$$

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