Generic System Design and Investigation of Solar Cooling Systems

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This Thesis is submitted to
Loughborough University, Loughborough,
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

November 2013

For mother earth

To my family

A contribution
to the improvement of human behavior
towards the environment

Abstract

This thesis presents work on a holistic approach for improving the overall design of solar cooling systems driven by solar thermal collectors. Newly developed methods for thermodynamic optimization of hydraulics and control were used to redesign an existing pilot plant. Measurements taken from the newly developed system show an 81% increase of the Solar Cooling Efficiency (SCE_{th}) factor compared to the original pilot system. In addition to the improvements in system design, new efficiency factors for benchmarking solar cooling systems are presented. The Solar Supply Efficiency (SSE_{th}) factor provides a means of quantifying the quality of solar thermal charging systems relative to the usable heat to drive the sorption process. The product of the SSE_{th} with the already established COP_{th} of the chiller, leads to the SCE_{th} factor which, for the first time, provides a clear and concise benchmarking method for the overall design of solar cooling systems. Furthermore, the definition of a coefficient of performance, including irreversibilities from energy conversion (COP_{con}), enables a direct comparison of compression and sorption chiller technology. This new performance metric is applicable to all low-temperature heat-supply machines for direct comparison of different types or technologies.

The achieved findings of this work led to an optimized generic design for solar cooling systems, which was successfully transferred to the market.

Ackknowledgements

This research was supported with funding from Loughborough University, Loughborough, and was undertaken part-time.

I would like to thank my supervisors Prof. Dr. Malcolm Cook (Loughborough University) and Dr. Uli Jakob for their great assistance during the whole research work.
Parts of this work were carried out when I was working at Solar Next AG at Rimsting, Germany. I am gratefull to SolarNext AG for providing the opportunity and facilities to undertake this work.

I would like to thank my family for moral support and patience that enabled me to complete this research work.

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Nomenclature

$\mathrm{A_{storage}}$	$[\mathrm{m^2}]$	Overall surface of storage
c_p	$\left[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right]$	Specific heat capacity at a constant pressure
$\widetilde{c_p}\Big\vert_{T_i}^{T_g}$	$\left[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right]$	Average specific heat capacity at a constant pressure of the temperatures T_i and T_g
COP_{con}	$[-]$	Conversion coefficient of performance, ratio of cooling output to the driving energy input including irreversible conversion of electrical work for driving the machine
$COP_{con\ el\ sorp}$	$[-]$	Equivalent coefficient of performance of a sorption chiller subsystem for direct comparison with the COP_{el} of a compression chiller
$COP_{con\ el\ sysWFC18}$	$[-]$	Equivalent coefficient of performance of a WFC18 absorption subsystem for direct comparison with the COP_{el} of a compression chiller
$COP_{con\ el\ sys1}$	$[-]$	Equivalent coefficient of performance of a sorption subsystem configuration 1 for direct comparison with the COP_{el} of a compression chiller
$COP_{con\ el\ sys2}$	$[-]$	Equivalent coefficient of performance of a sorption subsystem configuration 2 for direct comparison with the COP_{el} of a compression chiller
$COP_{con\ th\ comp}$	$[-]$	Equivalent coefficient of performance of a Compression chiller for direct comparison with the COP_{th} of a sorption chiller subsystem
COP_{el}	$[-]$	Electrical coefficient of performance for cooling applications, ratio of cooling output to the amount of electrical work/ capacity input

$COP_{el\ comp}$	$[-]$	Electrical coefficient of performance of a Compression chiller, ratio of cooling output to the amount of electrical work/ capacity input
$COP_{el\ sorp}$	$[-]$	Electrical coefficient of performance of a sorption chiller, ratio of cooling output to the amount of electrical work/ capacity input
COP_{th}	$[-]$	Thermal coefficient of performance for cooling applications, ratio of cooling output to the driving heat input
$COP_{th\ sorp}$	$[-]$	Thermal coefficient of performance of a sorption chiller, ratio of cooling output to the driving heat input
$COP_{th\ WFC18}$	$[-]$	Thermal coefficient of performance of a WFC18 absorption subsystem
E	$[\mathrm{J}] = \left[\frac{\mathrm{kg \cdot m^2}}{\mathrm{s^2}}\right]$	Energy
$E1$	$[\mathrm{J}]$	Energy of state 1
$E2$	$[\mathrm{J}]$	Energy of state 2
$E2$	$[\mathrm{J}]$	Energy of state 3
$\dot{E}_{irr}$	$\left[\frac{\mathrm{kJ}}{\mathrm{h}}\right]$	Irreversible power
$\dot{E}_{irr\ con}$	$\left[\frac{\mathrm{kJ}}{\mathrm{h}}\right]$	Irreversible power resulting from energy conversion
f_{con}	$[-]$	Energy conversion factor
$f_{con\ comp} = 1$	$[-]$	Energy conversion factor of a compression chiller, ratio of driving power to irreversible power
$f_{con\ sorp} > 1$	$[-]$	Energy conversion factor of a sorption chiller, ratio of driving power to irreversible power
$f_{con\ sysWFC18}$	$[-]$	Energy conversion factor of a WFC 18 absorption subsystem

g	$\left[\frac{m}{s^2}\right]$	Gravitational acceleration
h	$\left[\frac{kJ}{kg}\right]$	Specific enthalpy
h_i	$\left[\frac{kJ}{kg}\right]$	Specific enthalpy of mass flow rate $\dot{m}_i$
h_{ch}	$\left[\frac{kJ}{kg}\right]$	Specific enthalpy of charging mass flow rate during “first charging and last discharging” phase
h_{di}	$\left[\frac{kJ}{kg}\right]$	Specific enthalpy of discharging mass flow rate during “first charging and last discharging” phase
$h_{ch_{op}}$	$\left[\frac{kJ}{kg}\right]$	Specific enthalpy of charging mass flow rate during “charging and discharging cycles during operation” phase
$h_{di_{op}}$	$\left[\frac{kJ}{kg}\right]$	Specific enthalpy of discharging mass flow rate during “charging and discharging cycles during operation” phase
$\dot{h}_{ch,di}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific enthalpy rate of charging and discharging during “first charging and last discharging” phase
$\dot{h}_{ch,di_{op}}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific enthalpy rate of charging and discharging during “charging and discharging cycles during operation” phase
$\dot{h}_{HT_{in}}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific inflow enthalpy rate of the high temperature (HT) interface of an absorption chiller (generator)
$\dot{h}_{HT_{out}}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific outflow enthalpy rate of the high temperature (HT) interface of an absorption chiller (generator)
$\dot{h}_{LT_{in}}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific inflow enthalpy rate of the low temperature (LT) interface of an absorption chiller (evaporator)

$\dot{h}_{LT_{out}}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific outflow enthalpy rate of the low temperature (LT) interface of an absorption chiller (evaporator)
$\dot{h}_{MT_{in}}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific inflow enthalpy rate of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$\dot{h}_{MT_{out}}$	$\left[\frac{kJ}{kg \cdot s}\right]$	Specific outflow enthalpy rate of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$h(T_i)$	$\left[\frac{kJ}{kg}\right]$	Specific enthalpy at temperature T_i
H	$[kJ]$	Enthalpy
$H1$	$[kJ]$	Enthalpy of state 1
$H2$	$[kJ]$	Enthalpy of state 2
$H3$	$[kJ]$	Enthalpy of state 3
m_{ch}	$[kg]$	Charging mass
m_{di}	$[kg]$	Discharging mass
$m_{ch,di}$	$[kg]$	Charging and discharging mass of “first charging and last discharging” phase
$m_{ch,di_{op}}$	$[kg]$	Charging and discharging mass of “charging and discharging cycles during operation” phase
$m_{storage}$	$[kg]$	Storage mass
$\dot{m}$	$\left[\frac{kg}{s}\right]$	Mass flow rate
$\dot{m}_i$	$\left[\frac{kg}{s}\right]$	Mass flow rate of port i
$\dot{m}_{ch}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of charging unit during “first charging and last discharging” phase

$\dot{m}_{di}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of discharging unit during “first charging and last discharging” phase
$\dot{m}_{ch,di}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of charging and discharging units during “first charging and last discharging” phase
$\dot{m}_{ch_{op}}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of charging unit during “charging and discharging cycles during operation” phase
$\dot{m}_{di_{op}}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of discharging unit during “charging and discharging cycles during operation” phase
$\dot{m}_{ch,di_{op}}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of charging and discharging units during “charging and discharging cycles during operation” phase
$\dot{m}_{HT}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of the high temperature (HT) interface of an absorption chiller (generator)
$\dot{m}_{LT}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of the low temperature (LT) interface of an absorption chiller (evaporator)
$\dot{m}_{MT}$	$\left[\frac{kg}{s}\right]$	Mass flow rate of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
M	[kg]	Mass
M1	[kg]	Mass of state 1
M2	[kg]	Mass of state 2
M3	[kg]	Mass of state 3
$q_{0\ irr_{ch,di_{op}}}$	$\left[\frac{kJ}{h \cdot kg}\right]$	Specific irreversible heat of “charging and discharging cycles during operation” phase
Q	[kJ]	Heat
Q1	[kJ]	Heat of state 1
Q2	[kJ]	Heat of state 2

Q3	[kJ]	Heat of state 3
$Q_{0\ irr}$	[kJ]	Irreversible heat
$Q_{0\ irr_{ch,di}}$	[kJ]	Irreversible heat of “first charging and last discharging” phase
$Q_{biomass}$	[kJ]	Heat generated from biomass
$Q_{heat\ sinks}$	[kJ]	Heat consumed by all integrated heat sinks of a thermal system
$Q_{heat\ sources}$	[kJ]	Heat generated by all integrated heat sinks of a thermal system
Q_{HT}	[kJ]	High temperature (HT) heat supply of an absorption chiller (generator)
Q_{LT}	[kJ]	Low temperature (LT) cooling capacity of an absorption chiller (evaporator)
Q_{MT}	[kJ]	Medium temperature (MT) heat rejection of an absorption chiller (evaporator)
Q_{solar}	[kJ]	Solar thermal generated heat
$\dot{Q}$	$\left[\frac{\text{kJ}}{\text{s}}\right]$	Heat transfer rate
$\dot{Q}_{0\ irr}$	$\left[\frac{\text{kJ}}{\text{s}}\right]$	Irreversible heat transfer rate
$\dot{Q}_{0\ irr\ ch}$	$\left[\frac{\text{kJ}}{\text{s}}\right]$	Irreversible heat transfer rate of a sorption/ compression chiller resulting from electricity consumption of auxiliaries to drive the machine
$\dot{Q}_{0\ irr\ con}$	$\left[\frac{\text{kJ}}{\text{s}}\right]$	Irreversible heat transfer rate resulting from energy conversion of electricity to drive a sorption/ compression chiller
$\dot{Q}_{0\ irr_{ch,di}}$	$\left[\frac{\text{kJ}}{\text{s}}\right]$	Irreversible heat transfer rate of “first charging and last discharging” phase

$\dot{Q}_{0\,irr_{ch,di_{op}}}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Irreversible heat transfer rate of “charging and discharging cycles during operation” phase
$\dot{Q}_{0\,irr_{ch,di_{op}}}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Irreversible heat transfer rate of “charging and discharging cycles during operation” phase
$\dot{Q}_A$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Absorber heat transfer rate of an absorption chiller
$\dot{Q}_C$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Condenser heat transfer rate of an absorption chiller
$\dot{Q}_E$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Evaporator heat transfer rate of an absorption chiller
$\dot{Q}_G$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Generator heat transfer rate of an absorption chiller
$\dot{Q}_{HT}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Heat transfer rate of the high temperature (HT) interface of an absorption chiller (generator), heat supply of the absorption chiller
$\dot{Q}_{LT}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Heat transfer rate of the low temperature (LT) interface of an absorption chiller (evaporator), cooling load of the absorption chiller
$\dot{Q}_{MT}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Heat transfer rate of the medium temperature (MT) interface of an absorption chiller (absorber, condenser), heat rejection of the absorption chiller
$\dot{Q}_{biomass}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Heat rate, generated from biomass
$\dot{Q}_{heat\ sinks}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Heat rate, consumed by all integrated heat sinks of a thermal system
$\dot{Q}_{heat\ sources}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Heat rate, generated by all integrated heat sinks of a thermal system
$\dot{Q}_{solar}$	$\left[\frac{\mathrm{kJ}}{\mathrm{s}}\right]$	Heat rate, solar thermally generated
s	$\left[\frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}\right]$	Specific entropy

s_i	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific entropy of mass flow rate $\dot{m}_i$
s_{ch}	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific entropy of charging mass flow rate during "first charging and last discharging" phase
s_{di}	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific entropy of discharging mass flow rate during "first charging and last discharging" phase
$s_{ch_{op}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific entropy of charging mass flow rate during "charging and discharging cycles during operation" phase
$s_{di_{op}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific entropy of discharging mass flow rate during "charging and discharging cycles during operation" phase
$s_{HT_{in}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific inflow entropy of the high temperature (HT) interface of an absorption chiller (generator)
$s_{HT_{out}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific outflow entropy of the high temperature (HT) interface of an absorption chiller (generator)
$s_{LT_{in}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific inflow entropy of the low temperature (LT) interface of an absorption chiller (evaporator)
$s_{LT_{out}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific outflow entropy of the low temperature (LT) interface of an absorption chiller (evaporator)
$s_{MT_{in}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific inflow entropy of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$s_{MT_{out}}$	$\left[\frac{kJ}{kg \cdot K}\right]$	Specific outflow entropy of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$\dot{s}_{ch,di}$	$\left[\frac{kJ}{kg \cdot K \cdot s}\right]$	Specific entropy rate of charging and discharging during "first charging and last discharging" phase

$\dot{s}_{ch,di_{op}}$	$\left[\frac{kJ}{kg\cdot K\cdot s}\right]$	Specific entropy rate of charging and discharging during "charging and discharging cycles during operation" phase
$\dot{s}_{HT_{in}}$	$\left[\frac{kJ}{kg\cdot K\cdot s}\right]$	Specific inflow entropy rate of the high temperature (HT) interface of an absorption chiller (generator)
$\dot{s}_{HT_{out}}$	$\left[\frac{kJ}{kg\cdot K\cdot s}\right]$	Specific outflow entropy rate of the high Temperature (HT) interface of an absorption chiller (generator)
$\dot{s}_{LT_{in}}$	$\left[\frac{kJ}{kg\cdot K\cdot s}\right]$	Specific inflow entropy rate of the low temperature (LT) interface of an absorption chiller (evaporator)
$\dot{s}_{LT_{out}}$	$\left[\frac{kJ}{kg\cdot K\cdot s}\right]$	Specific outflow entropy rate of the low temperature (LT) interface of an absorption chiller (evaporator)
$\dot{s}_{MT_{in}}$	$\left[\frac{kJ}{kg\cdot K\cdot s}\right]$	Specific inflow entropy rate of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$\dot{s}_{MT_{out}}$	$\left[\frac{kJ}{kg\cdot K\cdot s}\right]$	Specific outflow entropy rate of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$s(T_i)$	$\left[\frac{kJ}{kg\cdot K}\right]$	Specific entropy at temperature T_i
S	$\left[\frac{kJ}{K}\right]$	Entropy
$S1$	$\left[\frac{kJ}{K}\right]$	Entropy of state 1
$S2$	$\left[\frac{kJ}{K}\right]$	Entropy of state 2
$\dot{S}$	$\left[\frac{kJ}{K\cdot s}\right]$	Entropy rate
$\dot{S}_{gen}$	$\left[\frac{kJ}{K\cdot s}\right]$	Entropy generation rate

$\dot{S}_{gen_{ch,di}}$	$\left[\frac{\mathrm{kJ}}{\mathrm{K \cdot s}}\right]$	Entropy generation rate of “first charging and last discharging” phase
$\dot{S}_{gen_{ch,di_{op}}}$	$\left[\frac{\mathrm{kJ}}{\mathrm{K \cdot s}}\right]$	Entropy generation rate of “charging and discharging cycles during operation” phase
$\dot{S}_{gen_{HT}}$	$\left[\frac{\mathrm{kJ}}{\mathrm{K \cdot s}}\right]$	Entropy generation rate of the high temperature (HT) interface of an absorption chiller (generator)
$\dot{S}_{gen_{LT}}$	$\left[\frac{\mathrm{kJ}}{\mathrm{K \cdot s}}\right]$	Entropy generation rate of the low temperature (LT) interface of an absorption chiller (evaporator)
$\dot{S}_{gen_{MT}}$	$\left[\frac{\mathrm{kJ}}{\mathrm{K \cdot s}}\right]$	Entropy generation rate of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
SCE_{th}	$[-]$	Solar (supply) cooling efficiency, ratio of cooling output Q_{LT} to total solar output Q_{solar}
SSE_{th}	$[-]$	Solar supply efficiency, ratio of direct usable solar energy Q_{HT} to total solar output Q_{solar}
t	$[\mathrm{s}]$	Time
T	$[\mathrm{K}]$	Absolute temperature
T_0	$[\mathrm{K}]$	Ambient temperature
T_i	$[\mathrm{K}]$	Absolute temperature of mass flow rate $\dot{m}_i$
T_A	$[\mathrm{K}]$	Absorber temperature of an absorption chiller
T_C	$[\mathrm{K}]$	Condenser temperature of an absorption chiller
T_E	$[\mathrm{K}]$	Evaporator temperature of an absorption chiller
T_G	$[\mathrm{K}]$	Generator temperature of an absorption chiller
$T_{HT_{in}}$	$[\mathrm{K}]$	Inflow temperature of the high temperature (HT) interface of an absorption chiller (generator)
$T_{HT_{out}}$	$[\mathrm{K}]$	Outflow temperature of the high temperature (HT) interface of an absorption chiller (generator)

$T_{LT_{in}}$	$[\mathrm{K}]$	Inflow temperature of the low temperature (LT) interface of an absorption chiller (evaporator)
$T_{LT_{out}}$	$[\mathrm{K}]$	Outflow temperature of the low temperature (LT) interface of an absorption chiller (evaporator)
$T_{MT_{in}}$	$[\mathrm{K}]$	Inflow temperature of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$T_{MT_{out}}$	$[\mathrm{K}]$	Outflow temperature of the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$\mathrm{U}_{\mathrm{storage}}$	$\left[\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}\right]$	Overall heat transfer coefficient of storage
V	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Velocity
$V_{HT_{in}}$	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Velocity of the mass inflow at the high temperature (HT) interface of an absorption chiller (generator)
$V_{HT_{out}}$	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Velocity of the mass outflow at the high temperature (HT) interface of an absorption chiller (generator)
$V_{LT_{in}}$	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Velocity of the mass inflow at the low temperature (LT) interface of an absorption chiller (evaporator)
$V_{LT_{out}}$	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Velocity of the mass outflow at the low temperature (LT) interface of an absorption chiller (evaporator)
$V_{MT_{in}}$	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Velocity of the mass inflow at the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
$V_{MT_{out}}$	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Velocity of the mass outflow at the medium temperature (MT) interface of an absorption chiller (absorber, condenser)
W	$[\mathrm{kJ}]$	Technical work
W_{el}	$[\mathrm{kJ}]$	Electrical work

$\dot{W}$	$\left[\frac{\text{kJ}}{\text{h}}\right]$	Work rate, power
$\dot{W}_{el} = P_{el}$	$\left[\frac{\text{kJ}}{\text{h}}\right]$	Electrical work rate, electric capacity
$\dot{W}_{el\,aux} = P_{el\,aux}$	$\left[\frac{\text{kJ}}{\text{h}}\right]$	Electrical work rate of the system considered, including all auxiliary devices, electric capacity
Z	[m]	Elevation
ΔT_{i-g}	[K]	Temperature difference between T_i and T_g
$\Delta T_{ig\,m-0}$	[K]	Temperature difference between the average of T_i and T_g and the ambient temperature T_0
ΔT_{HT}	[K]	Temperature difference between $T_{HT_{in}}$ and $T_{HT_{out}}$
ΔT_{LT}	[K]	Temperature difference between $T_{LT_{in}}$ and $T_{LT_{out}}$
ΔT_{MT}	[K]	Temperature difference between $T_{MT_{in}}$ and $T_{MT_{out}}$
$\eta_{Storage}$	[−]	Efficiency of storage

Subscripts

CC	Cooling Circuit
CDE	Carbon dioxide equivalent
CHP	Cogeneration heat and power (-unit)
COP	Coefficient of Performance
EGM	Entropy generation minimization
GLD	Generation Linking Demand
GUI	Graphical user interface
HC	Heating circuit
HDC	Heat Distribution Cooling
HM	Heat meter
HMI	Human machine interface
HT	High temperature
I/O's	Inputs and outputs
IN	Inlet/ Inflow
LCD	Liquid crystal display
LT	Low temperature
MT	Medium temperature
OUT	Outlet/ outflow
PCM	Phase change material (-storage)
PER	Primary energy ratio
PLC	Programmable logic controller
PT1000	Platin temperature sensor $(1000\Omega, \mathrm{T} = 0°\mathrm{C})$
SD card	Secure digital memory card
SCS	Solar cooling system
VSHP	Valve storage heat primary side
VSHS	Valve storage heat secondary side

1. Introduction

1.1 Background and motivation

As the world's population continues to grow, its hunger for energy is becoming more acute, thus putting an unsustainable strain on fossil fuel resources. One of the main contributors to this problem is the demand for cooling in buildings. Figure 1-1 illustrates the increasing market for conventional air-conditioning units.

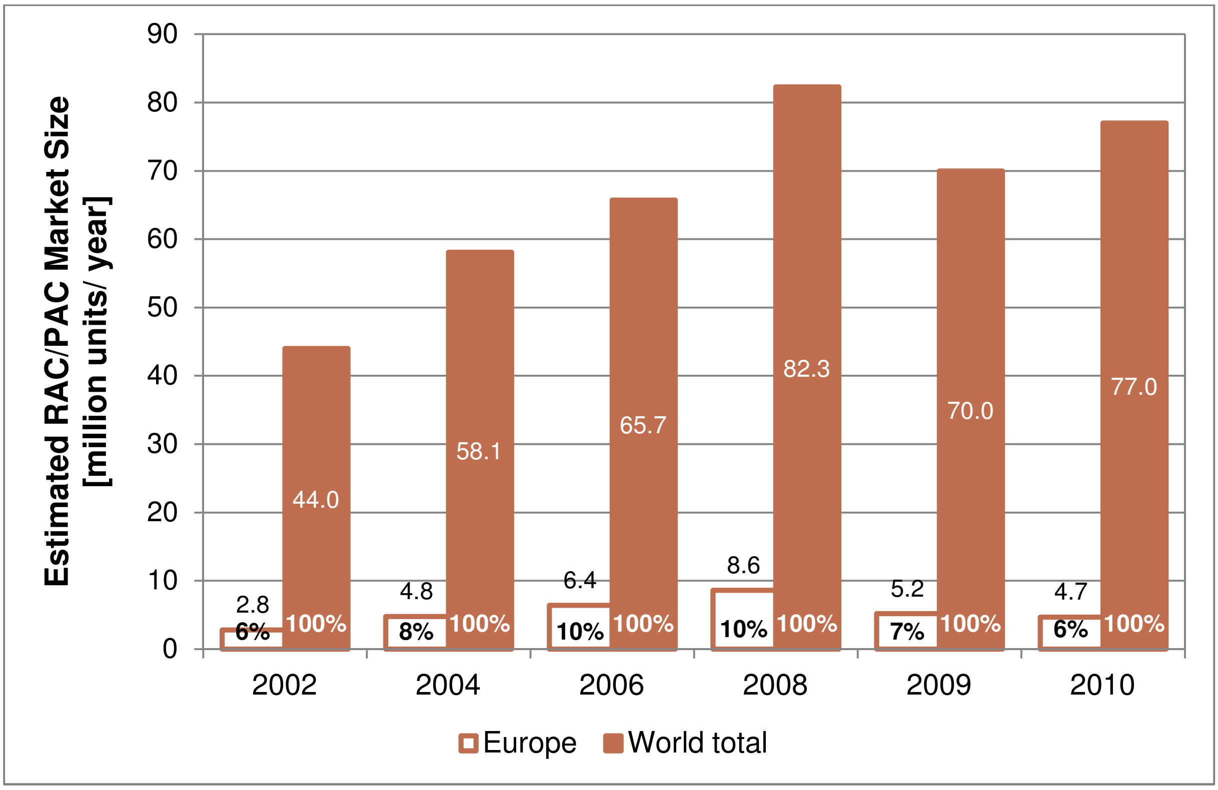


Figure 1-1: Cooling market development of conventional air-conditioning
(Source of data: Solem Consulting / JARN, 2011)

Renewable alternatives include solar-driven cooling systems. Generally, there are two different kinds of solar cooling methods: (i) electrically-driven solar cooling systems, for example, compression chillers driven by PV generated electricity; and (ii) thermally driven solar cooling systems, for example, sorption chillers driven by heat generated by solar thermal collectors (Hartmann, Glueck & Schmidt 2011). For the electrical systems, small-scale split-units are widely available and are mostly driven by fossil generated electricity. Due to their widespread use, these compression chillers are comparably cheap and easy to install. It is also possible to power these chillers using PV generated electricity. However, the high exergy content of electricity makes this an undesirable solution. Instead, electricity should be used only for those applications for which there is no alternative, such as, electrical motors, computers and illumination (Marletta, Evola & Sicurella 2008). Solar driven

sorption chiller systems offer the potential to save significant quantities of primary energy. Even if supplemented with a fossil-based system, primary energy savings from 38% to 53% are achievable (Pietruschka, Jakob & Eicker 2010). However, compared to electrical systems, the thermal systems are not yet established within the market (Langniss et al. 2007). Currently, very few systems have been installed around the world (Sparber et al. 2009). Such systems still require a significant investment of effort in order to ensure reliable and efficient operation (Jakob 2010).
The motivation for this research work results from the desire to make a contribution for an improved relationship with our environment. Sustainability is meant to be the key and renewable energy generation is identified to be one method to achieve this target.

1.2 Aim and objectives

The main aim of this work is to develop market-ready solar cooling systems for enabling the widespread application of this sustainable cooling method.
To achieve this target, the following objectives have been derived:

- Develop an applicable methodology for investigating complex structures
- Identify and develop adequate methods for analysis and design of thermal systems
- Optimize the performance of solar cooling systems concerning to technical, economical and environmental issues
- Develop a generic design for solar cooling systems to be transferred for various applications
- Develop validation methods for comparison and verification of solar cooling systems
- Provide solar cooling systems as a verified product for the market

This thesis is intended to make a significant contribution to thermal system design for sorption cooling applications. It is intended to bring solar thermal driven cooling systems from research to the market.

1.3 Methodology and content

After developing a method for holistic system design, the theory of nested systems was applied for analysing an existing solar cooling plant, leading to characteristics for an optimized generic design. Applying the achieved findings via product development delivered modular market available solar cooling systems, to be verified via novel methods for system comparison.

In chapter 2 recent research work concerning to sorption technology and investigation of solar cooling systems is presented. Chapter 3 describes a state of the art system to be analysed as a starting point for optimization. In chapter 4 a novel methodology for holistic systems engineering is applied to this research work. Chapter 5 describes the generic design for optimized solar cooling systems. In chapter 6, the implementation of this research work is presented via describing the product development process. Chapter 7 presents the development of novel performance metrics for comparison and verification of solar cooling systems. In chapter 8, the improved performance of the redesigned system is verified applying the novel performance metrics. Chapter 9 presents the market available products, resulting from this work. Chapter 10 summarizes the research findings and draws together the conclusions.

2. Literature review

2.1 Preamble

The purpose of this chapter is to describe the state of scientific and technical knowledge concerning solar cooling systems, starting with the idea of solar cooling in the 19th century to research and investigation in solar cooling systems in the 21st century.

In 1878, during the world exhibition in Paris, Augustin Mouchot presented the first system that was designed to achieve cooling via solar thermal energy (Jakob U. 2011). This demonstration solar cooling system, consisting of an ammonia water absorption chiller and a solar parabolic collector, was able to produce an ice block via applying solar thermal generated heat to drive the sorption process of an ammonia/ water absorption chiller (see Figure 2-1).

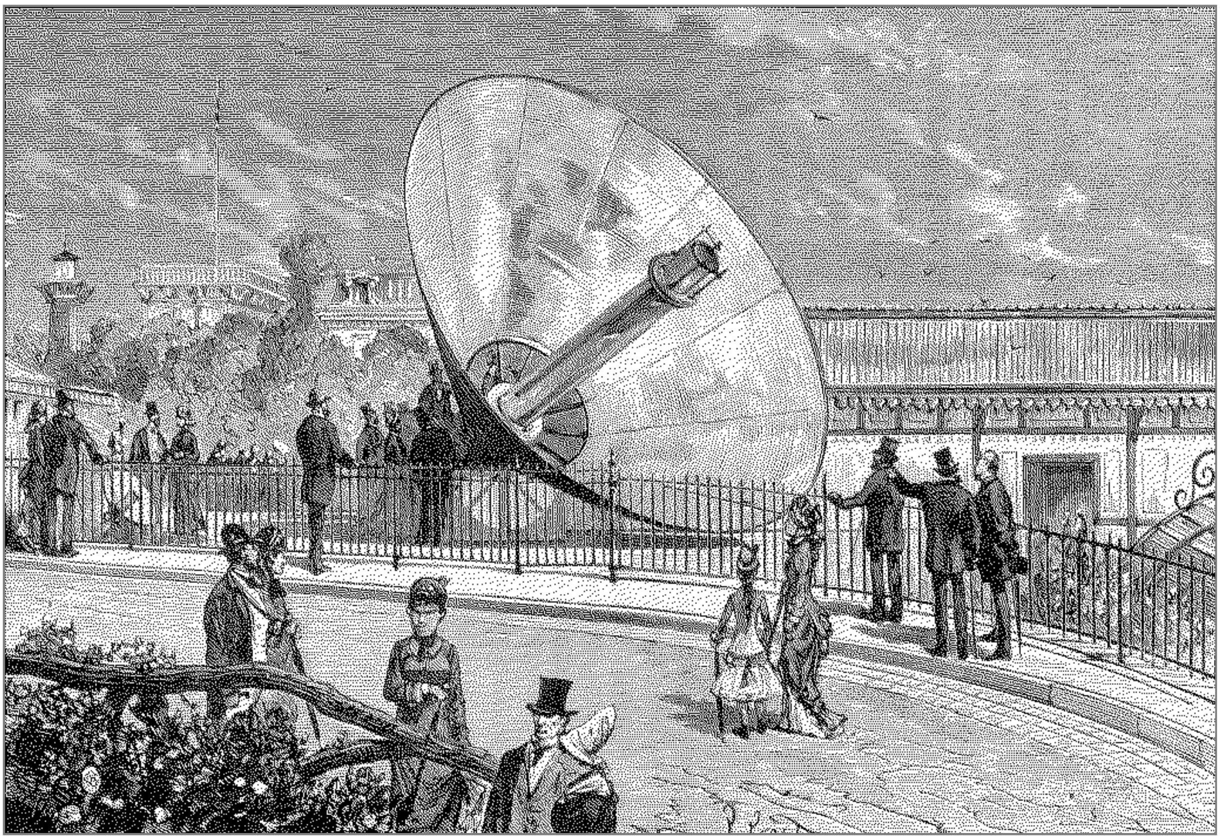


Figure 2-1: Augustin Mouchot’s solar thermal driven sorption system (Source: Butti 1981)

Almost one hundred years past until the first commercial applications were developed, leading to a new wave of research and investigation in solar cooling in the 21st century (Jakob U. 2011).

2.2 Recent investigations

Within this section, recent investigations concerning sorption cycles and solar thermally driven cooling systems are described.

In 1996, Wijeysundera illustrated the dependencies between maximum cooling load and maximum COP of absorption chillers. His research in performance limits of absorption cycles via thermodynamic analysis, lead to applicable fundamentals for achieving efficient operation of the sorption system (Wijeysundera 1996).

In 2005, Jakob investigated in ammonia/ water absorption technology (Jakob, De Montfort University. 2005). Simulation and field-testing during his research delivered detailed methods in modelling absorption cycles for further system and control development.

In 2003, Safarik proposed a recommended standardisation of solar cooling systems resulting from his research work in building simulation and a solar thermally driven absorption system (Safarik 2003). This work mainly focused on simulation models and the experimental investigation of components and subsystems such as the absorption chiller prototype and a PCM-storage system. Shortcomings of the solar cooling system such as a late start-up or poor system efficiency were mentioned briefly, leading to recommendations such as an improved COP_{th} of the chiller and lower heat losses of the storage system. Influence of controls was not considered.

Kohlenbach investigated the heat transfer of absorption chillers and control strategies of solar cooling systems applying experimental methods and simulation using TRNSYS (Kohlenbach 2006). Different control strategies for the solar thermal system, such as temperature difference-based control and radiation-based control were investigated, but no preferred control strategy was identified. He concluded that further research was required for achieving reliable and competitive solar cooling systems, mainly resulting from poor controls. Optimization based on the achieved findings was not conducted.

The simulation model of solar cooling systems presented by Eicker in 2009 delivered a strong influence of the control strategy to design and performance of the solar thermal system, leading to a strong dependency to the cooling load of the sorption chiller (Eicker, Pietruschka 2009).

Recent work by Pietruschka on simulation based optimization and experimental investigation in a solar cooling and heating system, delivers further findings from

simulation such as fan speed control and variable heat supply temperatures for the chiller lead to a higher total primary energy ratio (PER). He also states that an additional cooling back-up via compression chillers leads to a better primary energy efficiency compared to a heat supply back-up. As a result from simulation, he recommends an improved control design to provide speed control for some but not all actuators involved. Implementation or experimental validation of the recommendations was not applied (Pietruschka, De Montfort University. 2010).
Within his historical review of sorption cycles, Critoph specifies the key conditions for successful sorption technology consisting of technical, economical and even socio-political aspects (Critoph 2012).

In summary, these previous investigations in sorption technology and solar cooling systems imply a strongly recommended demand for optimized control and overall system design, including related conditions such as economical and environmental aspects.

Some manufactures offer packages of solar thermal systems and sorption chillers, inspired by the entry to the market of SolarNext AG offering chilli® Cooling Kits (Jakob 2013). Generic systems presented by the IEA SHC Task38 are based on the idea of a matrix for organising system components devised by the author of this thesis (see Figure 2-2 A and B).

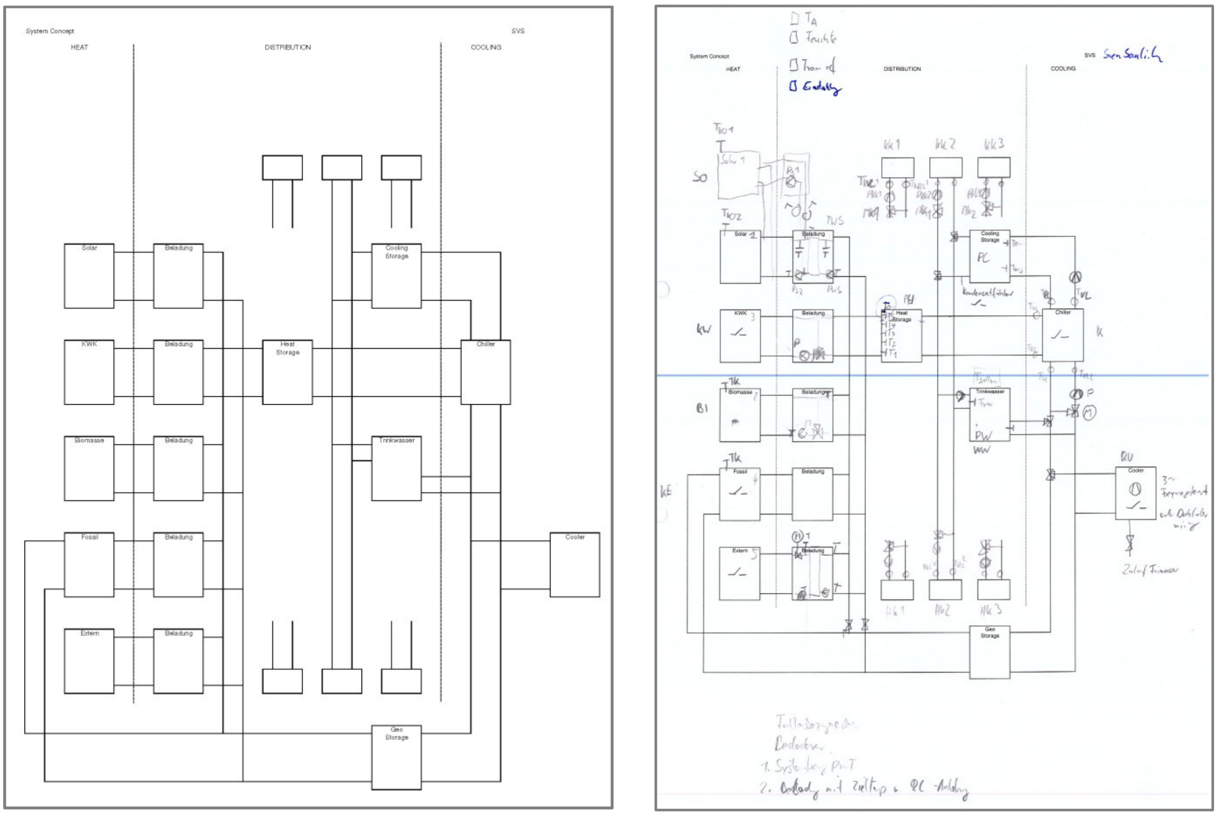


Figure 2-2 A and B: Modular generic concept for solar cooling systems devised and presented by the author during 2nd expert meeting of SHC Task 38 held April 23rd-25th 2007 in Aix-Les-Bains, France

This work was not finalised and did not include thermodynamic optimization or validation nor implementation and testing (Becker, Helm & Schweigler 2009).

Previous research in the field of solar cooling system design follows a similar methodology whereby an intuitively arranged test facility or pilot installation consisting of a solar thermal system and a sorption system is equipped with a measurement system. Then data collected is compared with a simulation model, and optimization of the system is mainly focussed on the model rather than on the real system. Concluded shortcomings are often not applied to optimize the system, leading to similar repeating suggestions for further research work such as an optimized control [e.g. compare (Ayadi et al. 2012), (Martínez et al)], and/ or optimized overall system design [e.g. compare (Riepl et al. 2012)]. The IEA SHC Task 38 monitoring results confirm the need for optimization of solar thermally driven sorption systems within the field (Jaehnig, Thuer 2011).

However, no sustainable attempt is made to optimize an overall solar cooling system, thus, clearly indicating a need for a novel approach to optimize solar cooling system design.

Furthermore, an integrated thermal system has not been presented by existing research, neglecting the correlations and dependencies between heat generation and sorption subsystems, and in case of solar thermal heat generation the role of the storage system as a link between generation and consuming units. When investigating in solar thermally driven cooling systems, the integration of the storage system is essential for high efficient and reliable operation of the entire system.

In 1977, Lavan and Thompson presented an experimental study of thermally stratified hot water storage tanks highlighting the correlation of thermal stratification within the storage and the extraction efficiency describing the ratio of thermal energy that can be drawn from a charged tank (Lavan, Thompson 1977). They described the effects of varying parameters such as port location, storage geometries and mass flow achieving extraction efficiencies up to 97%.

Wood et al. (1981) extended the investigation of stratified storage systems by a charging process and defined a one-dimensional diffusion model for describing the development of the thermocline depending on parameters such as fluid velocity and storage geometry. By considering former results from Lavan and Thompson (1977), he concluded that the charging and discharging efficiency of cylindrical storage systems is higher than for cubical storage systems due to no “dead zones” resulting from corners.

These previous investigations deliver fundamental findings for increasing the storage efficiency by enabling a good stratification within the tanks. However, the presented work assumed complete charging and discharging of the storage, leading to focus on perfectly stratified systems represented by a thin thermocline within the tank which separates the areas of different temperatures. It is obvious, that mixing, thermal diffusion or convection negatively affects the extraction rate during every complete charging and discharging cycle.

But operating a real system, charging and discharging is processed simultaneously and might not be completed more than once a day. Losses resulting from “preparing” the stratification cannot be avoided, but the frequency of establishing a thermocline can be reduced by decreasing the number of complete charging and discharging cycles. When harmonizing the amount of charging and discharging energy, the established stratification can be preserved during the whole operation period, leading to lower losses considering the whole operating period, and therefore enabling extraction ratios greater than 97% (see Figure 2-3).

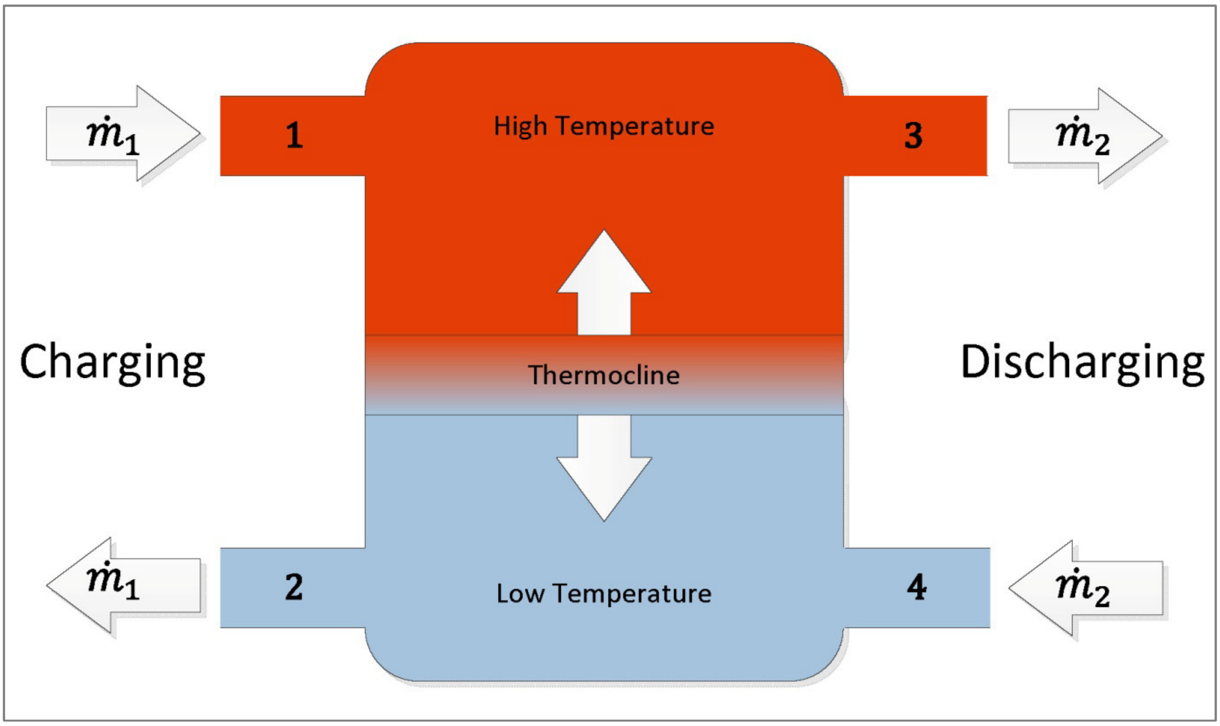


Figure 2-3: Principle of preserving existing stratification via harmonizing the charging and discharging process

This principle of reducing the frequency of establishing a thermocline by focusing on preserving the existing stratification is experimentally investigated within this work.

In 1991, Obert presented an energy supply concept with integrated solar thermal systems, including control strategies such as target temperature control (Riechert, Obert 1991). This work is helpful for system design because the control strategies presented enable system dependencies to be considered.

To create an overall thermal system via combining sorption subsystems with heat generation systems is one of the objectives of this research work. To verify results from investigation and development, adequate comparison methods are required.

For validating sorption cycles Pons et al. presented the thermal COP_{th} to be applicable for the comparison of different sorption systems (Pons et al. 1999). The focus on the performance of the sorption chiller limits its applicability when validating

solar thermally driven cooling systems. Therefore, the method needs to be extended by including further components involved such as the storage system and the solar thermal system.
In 2012, Eicker presented a method for the comparison of sorption and compression technology applying the primary energy efficiency (Eicker, Pietruschka & Pesch 2012). However, validation with primary energy performance metrics does not fully represent the value of decentralised heat generation for driving the sorption chiller, and falls short of being a representative comparison method when electricity is renewably generated to drive a compression chiller (Beccali et al. 2012).

Applied performance metrics to benchmark solar cooling systems are not standardized, and often require significant effort in measurement and calculating methods [e.g. compare (Napolitano et al. 2011) and (Nowag et al. 2012)].
Performance metrics for validating solar cooling systems should be simple to evaluate, concise and applicable to a variety of wide spread systems within the field. This, enabling an international accepted benchmarking of solar cooling systems.
Furthermore, existing validation methods are mainly focused on subsystems and components, confirming another objective of this work to investigate in comparison methods for an overall solar cooling system.

2.3 Summary of literature review

When the first apparatus implementing the original idea of solar cooling, was presented in the 19th century, surrounding conditions for a wide application of this technology were not given. Resulting from the population's increasing hunger for energy, the working principle of solar thermal driven cooling became an interesting field for scientists again.

Previous investigations into solar cooling systems have focused mainly on the system components such as the chiller, the collector, or the heat rejection units, and therefore have not considered the relation between supply and demand of an overall energy system about which there is limited published work. However, this correlation is extremely important for a highly efficient system with sufficient control.

Scientists such as Eicker and Critoph pointed out the importance of economical issues, to become sorption systems a mainstream technology. Standardisation, reliability and good usability of solar cooling systems are still unsolved tasks.

Considering the few research work done within the field of solar cooling system design, an existing pilot plant will be regarded within the following chapter for evaluating the state of the art of this technology.

3. State of the art of solar thermal cooling systems

3.1 Solar cooling pilot plant, Rimsting 2007

The purpose of this chapter is to show the state of the art of solar cooling systems, describing a pilot system from 2007, built in Rimsting, Germany to provide the cooling load for a single-storey office building occupied by the company SolarNext AG. Commissioning took place in March 2007. The system consisted of market available components with standard configurations, which means, that components such as storage tanks have “standard” insulation with a thickness of 10cm, and temperature sensors that are mounted via the available thermometer pockets inside the tank.

3.2 Description of 2007 pilot plant

The main heat source for driving the single-effect absorption chiller is a solar thermal plant with a gross collector area of 37 m². This is supplemented with a 30kW oil-fired boiler (Figure 3-1).

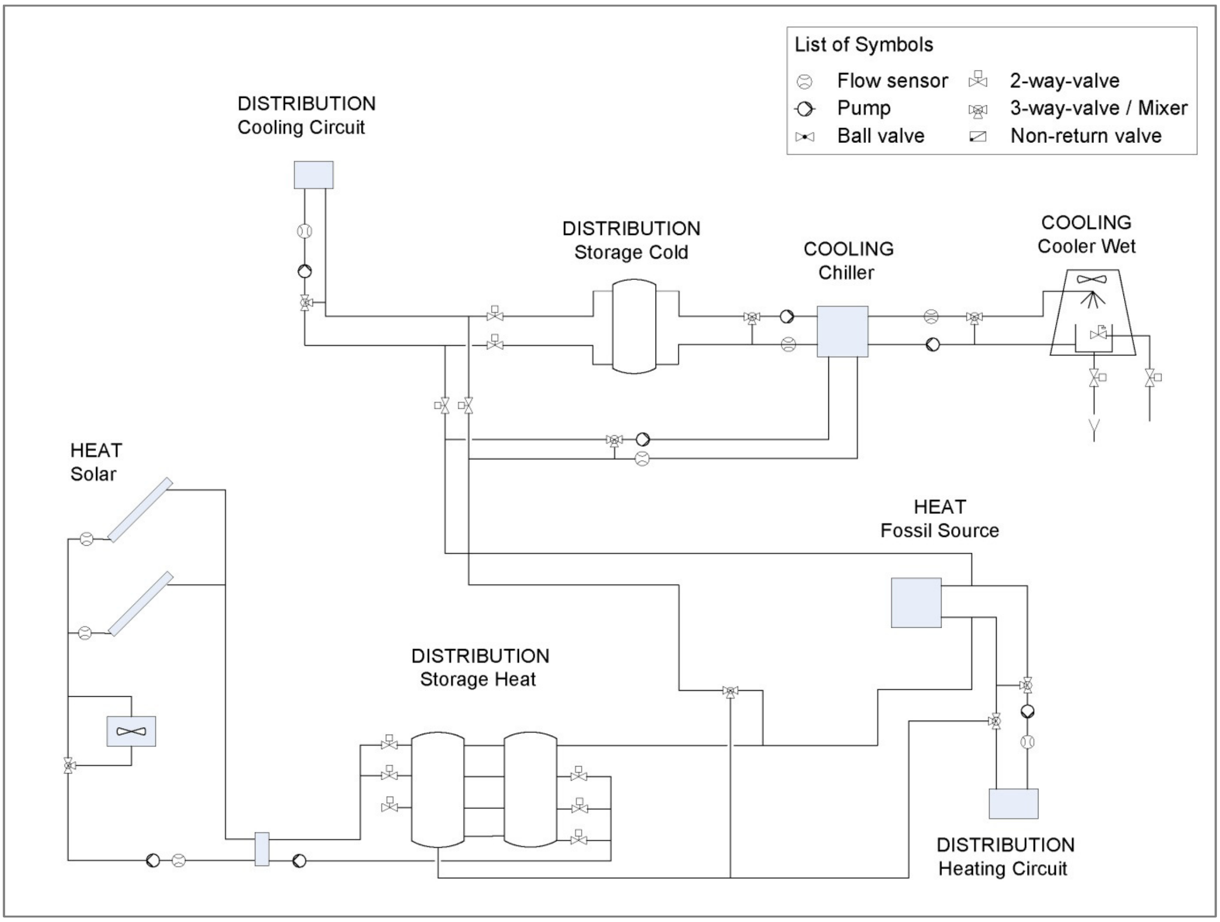


Figure 3-1: Hydraulic scheme pilot plant 2007 at office building SolarNext AG, Germany (Source: SolarNext AG)

The flat plate collectors were connected to three parallel groups with six collectors in series in each. The pipe connections were arranged according to the Tichelmannsystem (same length, same pressure drop and same flow rate for parallel collector groups). The solar thermal plant was extended in 2008 by a further 36 m² of vacuum tube collectors. Here, seven collectors in series were connected to three parallel groups. One primary pump supplies both collector areas with antifreeze fluid. As an active protection against overheating, an additional fan coil was installed outside the building within the primary solar circuit. In the case of no heating demand in summer, this meant that the generated solar thermal energy would not cause any damage to the plant by overheating any components. A plate heat exchanger separates the solar fluid from the heating circuit water. The secondary solar pump transports heating circuit water from the bottom of the hot water storage tank, through the heat exchanger and back to the top of the storage tank. To store the solar thermal energy, two tanks, each with 1,000 litres capacity were installed in parallel. For charging the hot water storage, the tanks were hydraulically separated via six 2-way valves into three levels ('top', 'middle' and 'bottom') which can be charged separately by opening and closing appropriate valves. Discharging of the solar loaded hot water storage tanks was managed by a return flow boost of the oil-fired boiler. This means that the return flows of heating circuit or sorption chiller supply were switched to the bottom of the storage tanks. Via the top of the storage tanks the solar thermal heated water flows to the return inlet of the oil-fired boiler. In the case of insufficient heating, the pre-heated water is heated further using the oil-fired boiler to provide the necessary heat demand. For cooling, an EAW Wegracal SE15 absorption chiller with the working pair lithium bromide and water, consisting of the refrigerant water and the sorbent lithium bromide, was installed. Heat rejection of the chiller is via the wet cooling tower EWK 036 from Axima. The evaporator of the absorption chiller is connected to a 1,000 litres cold water storage tank. To distribute the chilled water around the office building an additional cooling circuit supplies fan coils and chilled ceiling panels. This circuit can be used for both heating and cooling purposes by using four 2-way valves.

3.3 Control Installation

To manage the solar cooling system, four different controllers were installed. Each of them coordinates its part of the system without communication between the individual devices (see Figure 3-2).

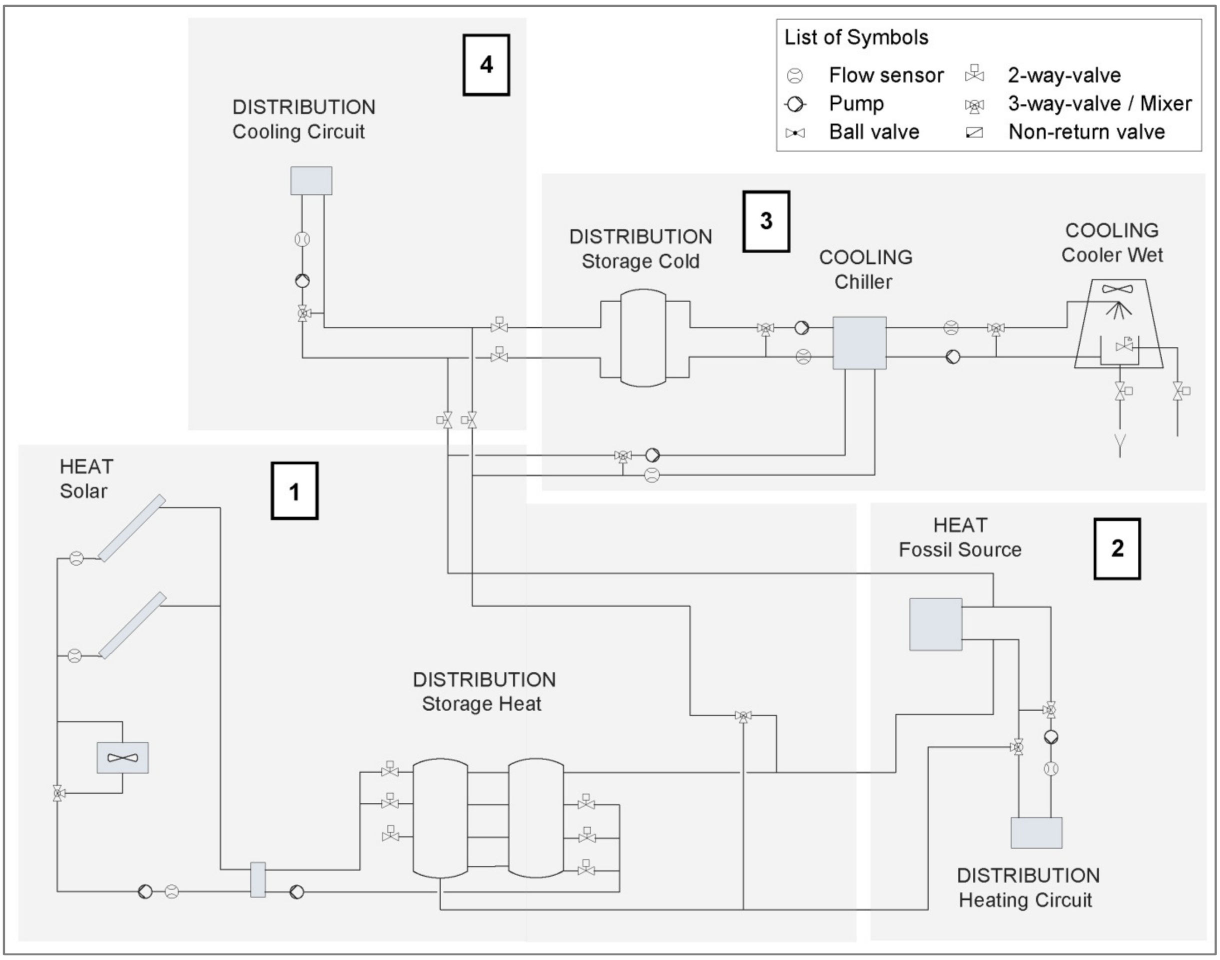


Figure 3-2: Control system of the 2007 pilot plant at office building SolarNext AG, Germany (Source: SolarNext AG)

The solar thermal plant, which includes charging and discharging of the hot water storage tanks and protection against overheating, was controlled using a Resol Solar controller ((**1**) in Figure 3-2). The solar thermal control strategy is based on temperature difference control. Hereby the operation of the primary and secondary solar pumps is controlled via the temperature difference between the collector and the storage system. The heating circuit and the boiler were managed by the onboard system ((**2**) in Figure 3-2). This includes generation of hot water by the oil-fired boiler outside temperature guided control for supplying the distribution of heat via radiators to cover the heating load of the building. The absorption chiller's onboard controller included control of the wet cooling tower as well as charging the cold water storage ((**3**) in Figure 3-2). In addition to running the heat supply pump, the cold water pump and the heat rejection pump, the fresh water supply and the fan control of the wet cooling tower is controlled. For distributing the cold water within the building, an additional cooling circuit consisting of fan coil units and chilled ceiling panels was controlled via a programmable logic controller (PLC) system ((**4**) in Figure 3-2). As a combined circuit which includes cold and hot water distribution, the installation structure can be used for cooling in summer and heating in winter.

3.4 Control Strategy

The solar thermal plant is controlled via temperature difference control, comparing temperatures between the solar collector and the hot water storage tank. If the temperature of the solar fluid within the collectors is higher than the hot water storage tanks, the primary pump is switched on. Running the secondary pump, heat is transferred to the fluid streaming from the storage through the plate heat exchanger back to the tanks.

Operating six 2-way valves, three inlet levels (Top, Middle, Bottom) can be charged. The actual level is chosen via temperature difference control between the solar fluid and the storage temperature. The system starts loading the low temperature bottom. With increasing solar irradiation leading to a higher temperature level of the solar fluid, the middle inlet is used until the temperature is high enough to load the top of the storage. The discharging of the stored solar heat is done via a temperature difference control between the top level temperature of the tanks and the return flow of the distribution circuits. For discharging, the fluid always streams through the oil-fired boiler to be able to provide a sufficient temperature for the heating circuits. A return-flow boost is a simple technique to combine existing heat sources with solar thermal plants because of low hydraulic and control effort. To supply the sorption chiller, the oil burner's control system has to be set to manual mode with a static temperature set point. Supplying the chiller without solar thermal energy within the storage system is not possible, because the heat supply pump is controlled by the chiller's control system. The sorption chillers onboard control starts the cooling mode, considering temperatures of heat and cold storage as well as the demand of the PLC-controlled cooling circuit. The heat supply pump is operated if temperatures of the heat and of the cold storage are higher than the adjusted set points. This signals sufficient heat supply on the one hand and demand for cooling on the other hand. Reaching an internal temperature level of the solution within the generator, the heat rejection pump and the cold water pump are operated. The sorption chillers operation ends with complete charging of the cold storage, insufficient heat supply or having no demand from the cooling circuit. Similar to the boiler's onboard control, the PLC managing the cooling circuits calculates the supply temperature depending on the outside temperature. In addition, the dew point is considered to avoid condensate on piping and chilled ceilings. This function is implemented via a sensor mounted at the inlet piping. Switching from cooling to heating mode, is done by a manual switch.

3.5 Short-comings of the 2007 pilot plant configuration

The hydraulic installation as well as the implemented controllers represents different subsystems, each focusing on a part of the system. The overall perspective is missing. Communication for signalling demand between the control systems is limited to one dry contact between the PLC and the chiller. Parts of the system have to be operated manually. The coordination of all these tasks is missing, as well as an optimized operation of each specific unit. The applied control strategies are limited to manual set points, temperature difference control circuits and a return flow boost. Reliability, efficiency and monitoring of the system are poor, and need to be improved.

3.6 Summary of pilot plant

Based on fundamentals and findings of previous investigations, in 2007 an operative state of the art solar cooling system was built to demonstrate the feasibility of applying this working principle via available components. The identified shortcomings of this system represent an important input for this research work.

As surrounding conditions such as the increasing demand for sustainable and environmental-friendly technologies became sufficient and technology fundamentals seem to be investigated, the step forward to market-ready solar cooling systems will be attempted by this research work.

4. Design methodology

4.1 Preamble

The purpose of this chapter is to identify an adequate methodology for designing solar cooling systems.
In contradiction to the continuous growing demand for "green technology", renewable cooling technology is not yet established within the market. Reasons for this are technical weakness and high investment costs of existing solar driven sorption systems. To succeed in competition with traditional technology, the solar thermally driven systems need to become much more attractive. The challenge to develop market-ready solar cooling systems requires efficient and concise methods for the investigation and development process.

4.2 Approach for the development of optimized solar cooling systems

This section describes the approach for developing improved solutions for multilayer affected systems. Previous investigations in solar cooling systems focused on components and subsystems such as the correlations between the sorption chiller and the heat rejection system. Compared to this limited perspective this work claims to consider all parts of the system. The small amount of research work done within this specific field does not give adequate methodologies for this approach. For the successful implementation of the general idea of solar cooling systems, this market-oriented methodology needs to be developed first.
One of the objectives of this research is to identify basic conditions, which will enable the definition of standards for improved system design. Therefore, the strategy for scientific success from this approach consists of evaluating applicable elementary methods. This process of finding, evaluating and modifying adequate scientific methods needs to be guided via an underlying fundamental philosophy. Combining technical, ecological and economical aspects leads to a holistic approach to achieving sustainable results.

4.2.1 Holistic thinking

Holistic thinking involves including all perspectives and influencing factors. Transferred to investigational work this philosophy suggests the scientists desire to fulfill various claims consisting of technical, economical, social and environmental aspects. Beside the opportunity to invent sustainable solutions, holistic thinking also contains the risk of over complicating the system being considered and therefore preventing viable solutions. To identify relevant aspects of holism, which are applicable for this work, the historical development of holistic thinking is now outlined. Gloy (1996) summarized the evolution of holistic thinking during the 19th and 20th century. She stated that the ideas of holism developed during the 19th century have been pushed back by the rise of the exact science within the 20th century. No more than in the recent past have environmental driven understandings favoured the idea of holism. This new paradigm displaces the old mechanical approach which indicated even organic systems to physical and chemical rules. Influenced by thoughts about self-organization and the chaos theory, ecological holism integrates single pieces to comprehensive complex structures, and goes further to an even more complex network.

The mechanical paradigm is represented by identifying the smallest components of the problem. The holistic approach begins with the whole and explains the parts based on the entire correlations. Both directions of action are helpful perspectives for scientific work.

The ethical perspective towards holism leads to ecological ethics, consisting of the question of how to live without changing or manipulating the environment. These ecological ethics fail by self-contradiction. Because nature includes evolutionary and therefore always changing conditions and characteristics, the deep human desire for fixing present states is the main contradiction, and does not reflect reality, but a global idyll. Solving this conflict leads to protection of nature on the one hand and development by innovation on the other.

This philosophy of dynamic holism is significant for this research, as it represents a dynamic and joint principle, which combines evolution of nature with sustainable innovation by mankind.

Transferred to scientific work, certain theoretical aspects of holism lead to three basic characteristics of a holistic approach towards thermal system design:

1. the system specifies the attributes and correlations of its parts, or vice versa – single parts of a system are modified by the whole system.
2. the whole system is more than the sum of its parts, through combining single parts, additional emergent characteristics are formed.
3. the whole system is a living organism, which not only consists of fixed attributes, but is also able to change and develop characteristics.

This holistic design approach delivers the necessity of finding fundamental methods for analyzing complex structures and correlations. Following this philosophy, the effect of emerging new attributes within a system, or because of a system design, will be considered. Furthermore, adequate principles to describe dynamic processes have to be identified.

4.2.2 Elementary scientific methods for holistic investigation and development

Within the following, elementary scientific methods are considered applicable for the holistic approach of this research.

Abstraction

A holistic approach facilitates the practice of including all perspectives and relevant information for investigation and development into the research methodology. But without a systematic simplification, the variety of components and applications would oversize the system being considered. The abstraction of complex structures and systems is one basic method for the holistic analysis of thermal energy systems. Charles S. Wasson defines abstraction as "*An analytic representation of an entity for a specific purpose in which lower level details are suppressed*" (Wasson 2006). Abstraction enables the concise and systematic identification of essential attributes, which can lead to general correlations and rules.

Analysis and synthesis

Analysis and synthesis are common methods for the investigation and development process (Pahl 2007). Analysis is clearly understood as a systematic method to identify characteristics and attributes of the examined subject. To form a system from abstracted models with specific attributes is defined as synthesis. Analysis and synthesis are methods applied one after the other. Transferred to a holistic approach, the procedure of analyzing thermal systems has to contain a component perspective as well as a system perspective. Holistic synthesis means to develop the optimum combination of component-oriented characteristics with system-oriented attributes. Moreover, the synthesis of single components to a system will generate emerging attributes.

To include dynamic aspects within the development process, the analysis -synthesis procedure has to be conducted a minimum of twice. Emerging system characteristics as a result of the synthesis process itself have to be analyzed again, concerning to their impact on components and system architecture.

Methods of reasoning – Abduction - Deduction – Induction

Scientific work includes abductive, deductive and inductive methods, which normally are used intuitively. Charles Sanders Peirce describes the methods of reasoning as follows: "*Deduction proves that something **must be**; Induction shows that something **actually is** operative; Abduction merely suggests that something **may be***" (Peirce 1974).

Deduction is based on existing rules and leads to expected results, as opposed to the inductive method of reasoning, which starts with results and leads to rules. Both methods are based on a higher number of similar results which allow the definition of a rule or vice versa. The abductive method is often described as a "guess". Only one result can lead to a hypothetical rule. Therefore the abductive method is often meant to enable the development of new rules and correlations.

Albert Einstein described the method of a theorist with deductive reasoning based on known principles. But in his opinion the main competition lies in identifying the fundamental principles and rules. He describes the abductive method of defining principles with : "…*the scientist has to learn fundamental principles from nature by identifying general characteristics from a large complex of experienced facts, which could be expressed in a concise way…"* (Einstein, Seelig 1959).

For investigation and development of improved thermal systems the application of the methods mentioned is essential.

Experiences and measurement results allow hypothetical rules via abduction. This guessed rule leads to deductive results, which can be verified by an inductive rule. If this rule is not applicable or insufficient, the process starts again with another abductive guess. For this work, abduction is identified to be a creative method to develop new rules and principles.

Emerging effects transferred to thermodynamics

Spontaneously formed new characteristics of systems are emerging attributes.

Those are, for example, synergies resulting from a "good combination" of single components. For thermal systems this effect could lead to improved overall system efficiency. Here, the quality of dynamic processes is described via the second law of thermodynamics. Entropy generation is the "negative" emerging phenomena of thermodynamics. The rate of generated entropy is proportional to the rate of irreversible and therefore "useless" energy. An ideal or "good combination" of single components can be described with a minimum of entropy generation.

Efficient system design by the method of entropy generation minimization (EGM)

Dynamic holism includes evolution through the ongoing change of the environment. This aspect is described in thermodynamics via the irreversibility of processes. The direction of the process is given by an ongoing generation of entropy, represented by time. For the inclusion of dynamic processes as well as for evaluating the most efficient design methods, entropy analysis is essential for improved results.

Bejan describes maximum power with a minimum entropy generation rate and sets "Entropy Generation Minimization" (EGM) equal to "thermodynamic optimization" (Bejan 1996). In Figure 4-1 the two-dimensional approach for the EGM-method is illustrated. Initially the method has been applied to complete systems, and then found its applications in heat transfer for components such as heat exchangers and solar collectors.

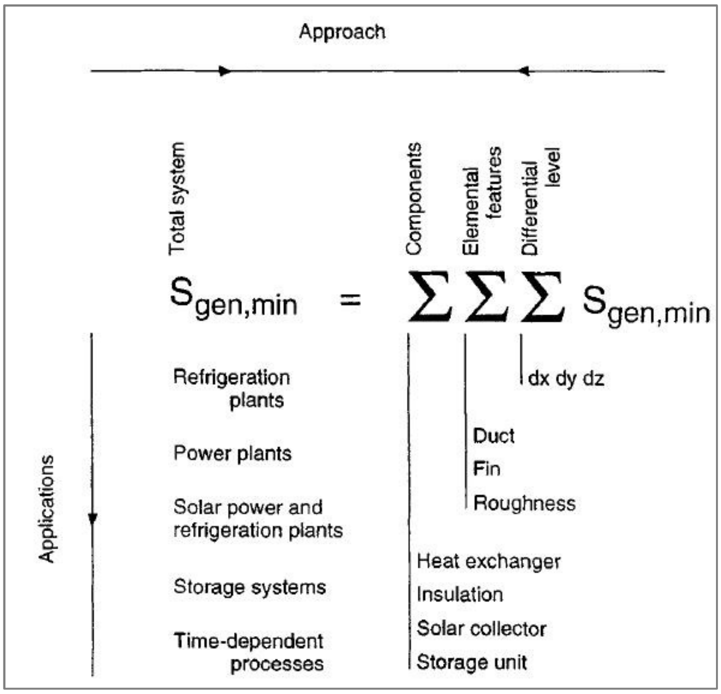


Figure 4-1: Two-dimensional structure of EGM – System and component approach (source: Bejan, 1996)

Within this research the EGM-method is transferred to thermal system design guidelines for the development of improved solar cooling systems. This method represents the inclusion of dynamic holism as well as the aim for high efficient solutions for system design.

4.2.3 Engineering methods for holistic development

There is a need for a methodology which applies fundamental methods for this work while respecting the holistic approach. This indicates that the strategy for proceeding has to include all relevant steps in an efficient and concise order.
To identify proven proceedings, established product development processes and engineering methods are reflected within the following.

Product development and systems engineering

The processes of product development usually include steps for analysis and synthesis as well as checks and acts on variations from target achievement. In addition to pure technical issues these methods also aim to integrate economical tasks. Market and customer needs are the starting point for successful product development.
Product marketing is understood as a combination of product, price, promotion and performance. This integrated view helps to investigate and develop technologies in such a way that market needs are included from the beginning of the process. A very structured and detailed method for the product marketing process is given by Koppelmann. The process starts with market analysis, design analysis and distribution aspects and ends with corrections to ensure target achievement (Koppelmann 2001). The relevance for this work especially lies on linking identified demands to specific product requirements via claim and embodiment analysis. To ensure an overall perspective, the multidimensional demands are categorized by technical and product aspects, customer oriented claims and distribution demands. Identified demands are then transferred to specific product requirements. Regarding external restrictions and available technologies, the generated requirements lead to a specific combination of system attributes.
Pahl delivers an even more detailed design process. After a common clarification phase, the design strategy consists of *conceptual*, *embodiment* and *detail* design phases (Pahl 2007). The conceptual design starts with a specification and ends with a concept for further development. This phase includes a helpful methodology for the development of functional structures, which is relevant for the analysis of solar cooling systems. The embodiment phase starts with the developed concept and

leads to a definitive layout. The basic rules for the embodiment of design are clarity, simplicity and safety. Following these rules means to cover the main objectives in technical, economical and environmental dimensions. The design phase is completed with the detailed design including input for production and the completion of documentation.

This very detailed version of the product development process gives helpful details and methods which can be transferred to this work.

A more general methodology is presented by Haberfellner. The “Systems Engineering”-philosophy is based on a system-oriented perspective and a general principle for proceeding (Haberfellner, Daenzer 1994). This approach includes methods for holistic analyzing, modeling and proceeding for complex systems. The principle for proceeding describes the main phases of the development process while single steps follow a general micro-logic for proceeding.

A future prospect of engineering methods is given by Hastings. Therefore the improvement of existing methodology will consist of simplification via focusing on a small number of methods which can be applied to many types of engineering systems (Hastings 2004).

In summary, established engineering methods have similar structures guiding through the development process. Inspired by the manifold methods given by established processes, a “good combination” of proceeding elementary methods and principles has to be created.

4.3 Analysis based on Nested Systems

For a holistic analysis, correlations and dependencies between solar cooling systems, environmental and market aspects have to be considered. To achieve a better understanding of multidimensional systems, a theory of nested systems was created to define the area of analysis and its system borders. The theory is based on a few simple rules, and is applicable for analysis and synthesis.

The main principles for describing multilayer systems with this theory are:

1. each system includes subsystems which them self consist of further parts;
2. all systems are interacting with each other; and
3. the combination of systems leads to emerging effects (positive and negative).

The application of this theory for the analysis of solar cooling systems delivers a specific model representing the structure of surrounding and integrated systems for this work (see Figure 4-2), leading to the methodology for this novel approach.

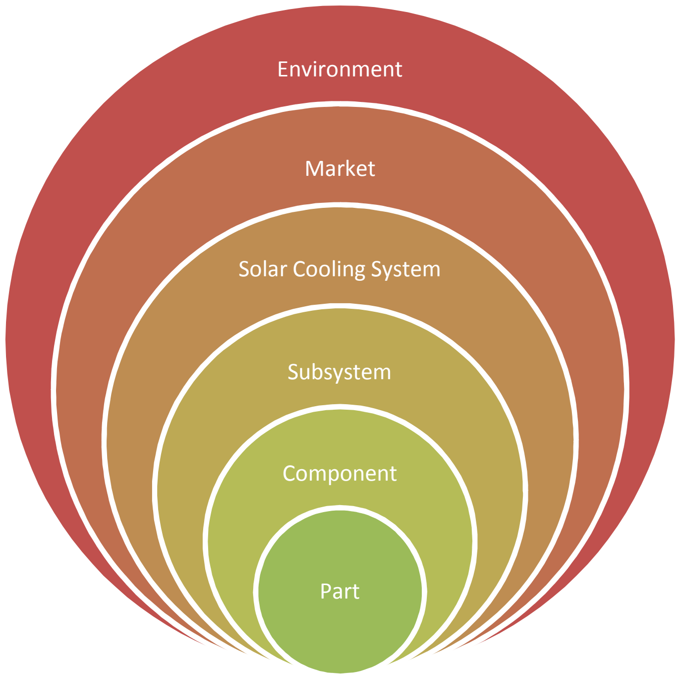


Figure 4-2: Model of nested systems – surrounding and integrated systems

This picture of multi-dimensional systems includes natural and artificial systems as well as unchangeable and designable aspects. As shown in Figure 4-2, a solar cooling system is part of upper-level systems such as the market and the environment. The solar cooling system itself consists of lower-level systems such as subsystems, components and single pieces. For identifying and describing correlations between the several dimensions, the theory of nested systems allows bottom-up and top-down interaction, which may consist of direct dependencies between the systems and/or chains of direct correlations between several system levels.

To achieve the target of optimized solar cooling systems, identified dependencies must lead to requirements for the novel system design. Therefore, upper-level and lower-level aspects have to be transferred to the investigational level of designing solar cooling systems (see Figure 4-3).

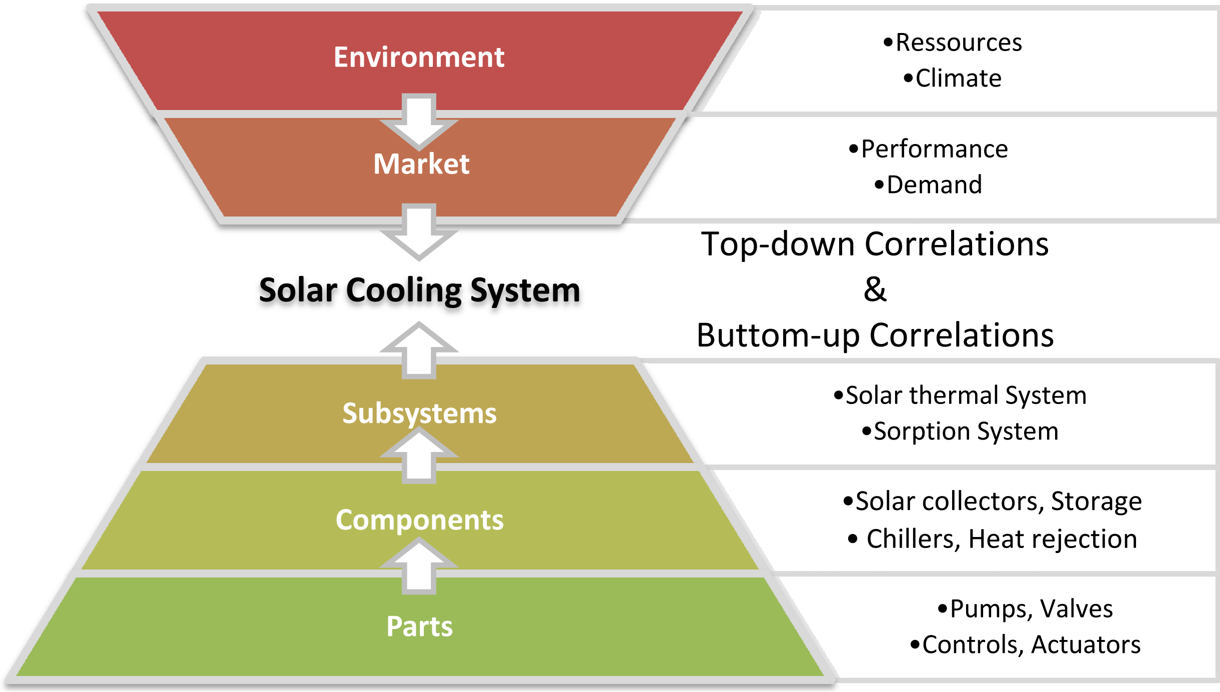


Figure 4-3: Transfer of correlations to investigation level

This specific model based on a theory of nested systems leads to an efficient and concise proceeding without over sizing the regarded system.

4.4 Analysis of system architecture from existing systems via HDC-modeling

As a starting point, the system architecture of solar cooling systems is analyzed based on the demonstration plant installed in 2007. In order to understand structural correlations clearly, the heat flow within the system is described here in detail. This functional analysis is processed using the hydraulic scheme of the solar cooling system. In order to achieve an informative heat flow chart, the main components are considered from a system perspective. Each component is described based on its function for the heat flow within the system. This method is processed by combining the hydraulic connectivity with possible functions of the existing control system, which leads to a declaration of the components thermal energy interfaces. Here, the interface for an outgoing heat flow is declared as “heat source”, and an interface for an incoming heat flow is declared as “heat sink” (see Figure 4-4). In a second step, “sources” and “sinks” are connected to illustrate the heat flow. For different operation modes of the system (heating or cooling), different colours are used for drawing the specific heat flows between the components. Red marked heat flows are only active during heating, blue marked heat flows describe heat flows during cooling and orange marked heat flows are active during both operation modes.

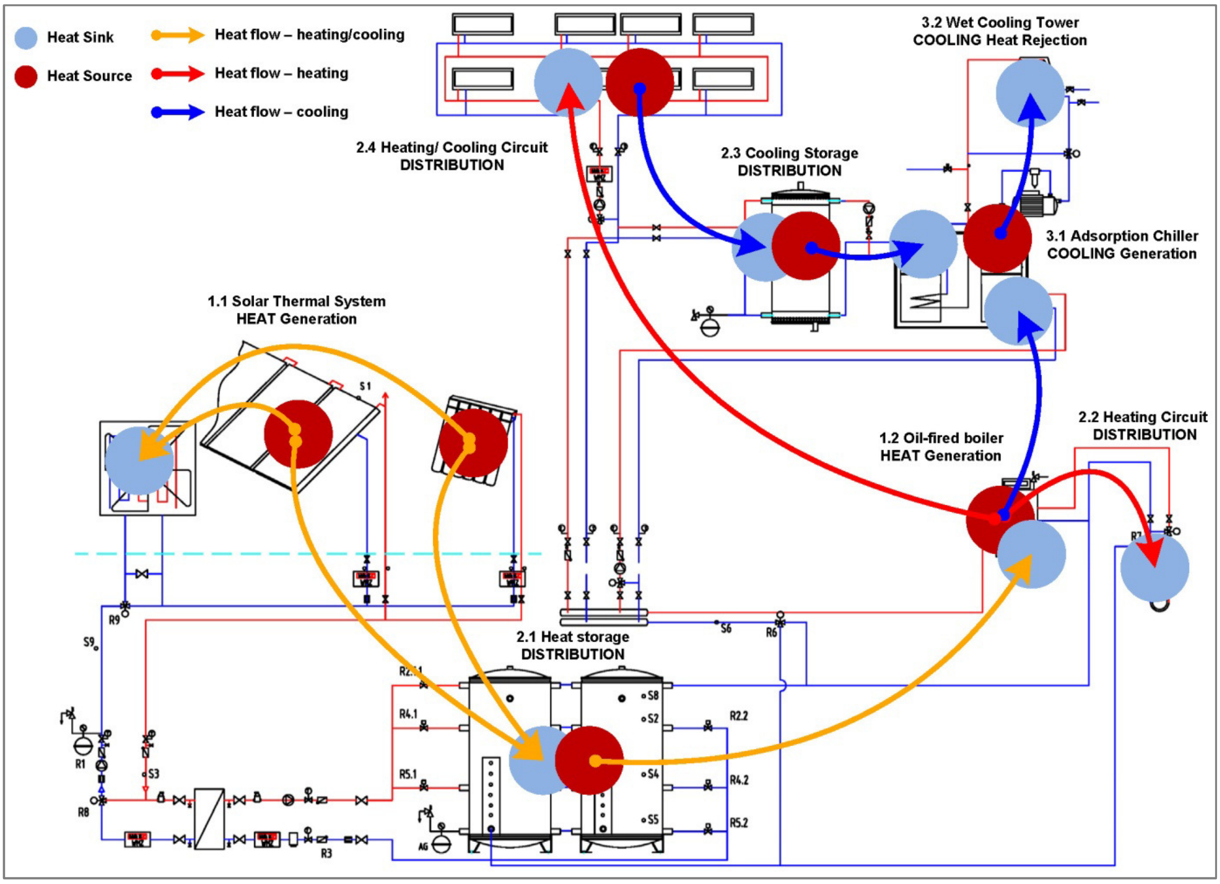


Figure 4-4: Analysis of heat flow and classification of components

The heat flow method enables the classification of the main components depending on their thermal functionality for the system. These are HEAT generation, the DISTRIBUTION of heat and COOLING (HDC). Abstracting the 2007 pilot system firstly leads to a heat flow model consisting of components (see Figure 4-5). By classifying to segments, a general heat flow model for solar cooling systems was developed.

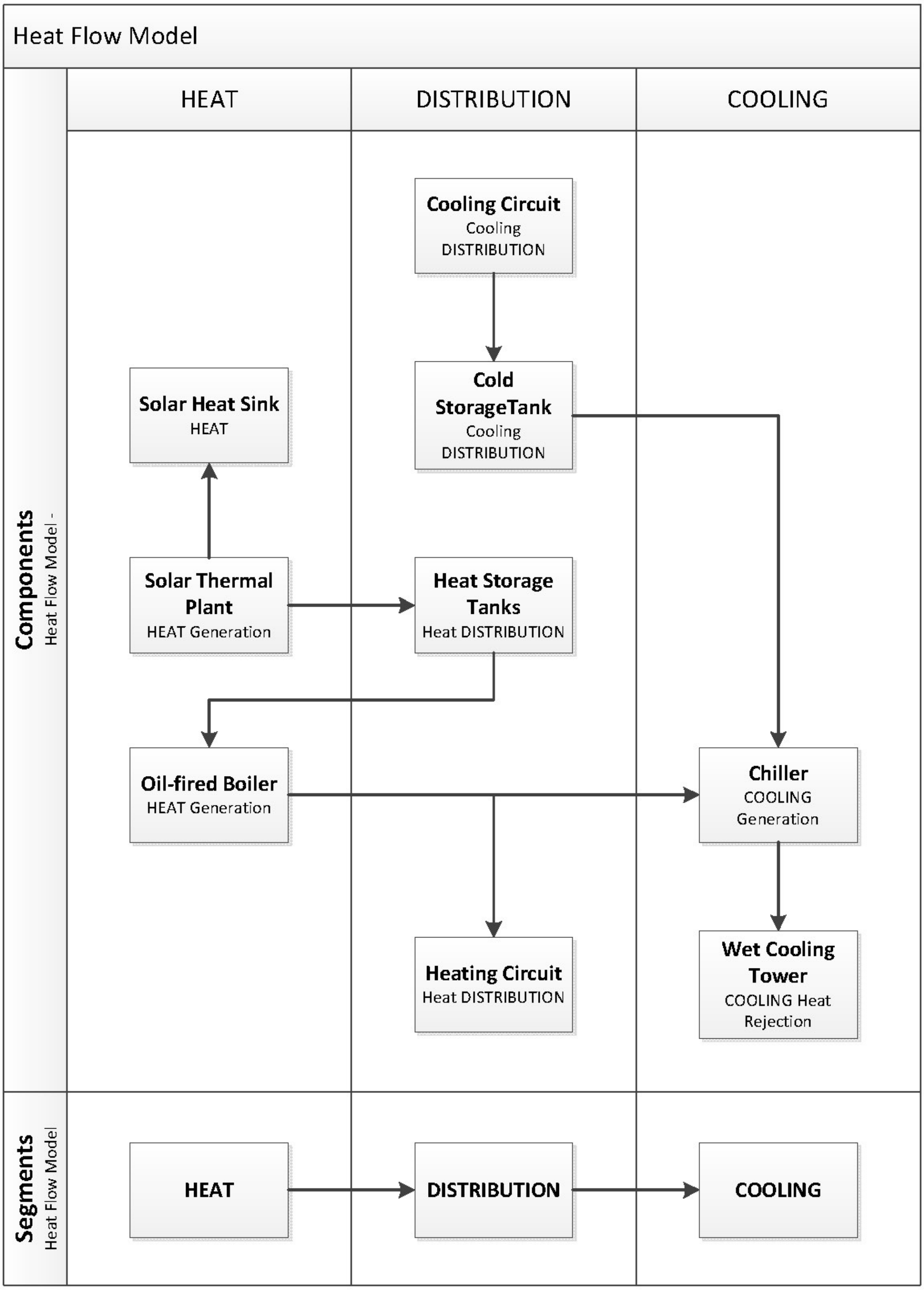


Figure 4-5: Heat flow model components & segments

With a high degree of simplification, a huge variety of potential applications and the inclusion of the main functionality of solar cooling systems, the HDC-model consisting of segments is applied for further analysis.

4.5 Analysis of surrounding systems

Within this section the surrounding, upper-level systems “environment” and “market” are considered following the theory of nested systems described in section 4.3.

4.5.1 Environmental aspects

The focus within this section is correlations between the surrounding environment and an integrated solar cooling system (see Figure 4-6).

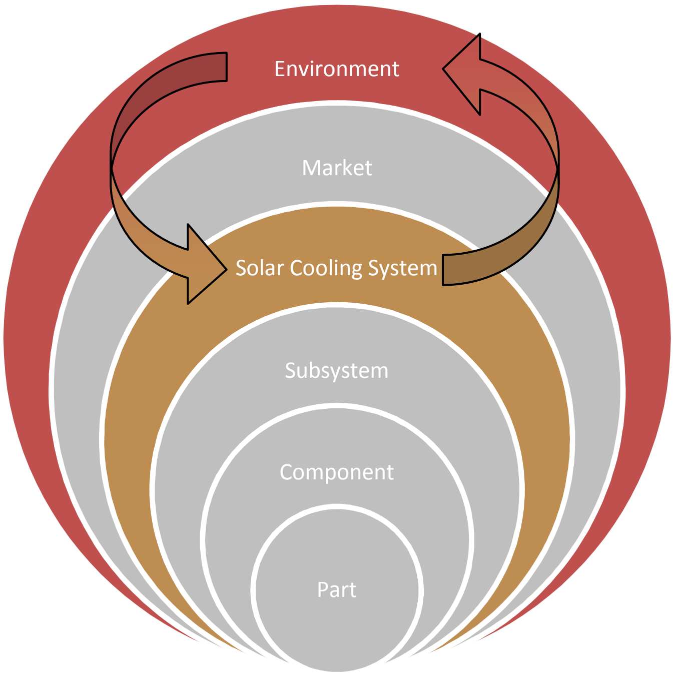


Figure 4-6: Model of nested systems – environment & solar cooling system

Relevant environmental aspects for system design are those which impact on a solar cooling system or vice versa. The nature of the impact considers whether the particular environmental aspect can be influenced by system design, or directly leads to necessary attributes for preventing negative impact by the particular environmental conditions. For the development of sustainable solutions, identified aspects have to be analyzed for the whole life cycle of a solar cooling system. This includes correlations with the environment during manufacture, operation and disposal. Figure 4-7 illustrates identified aspects for system design.

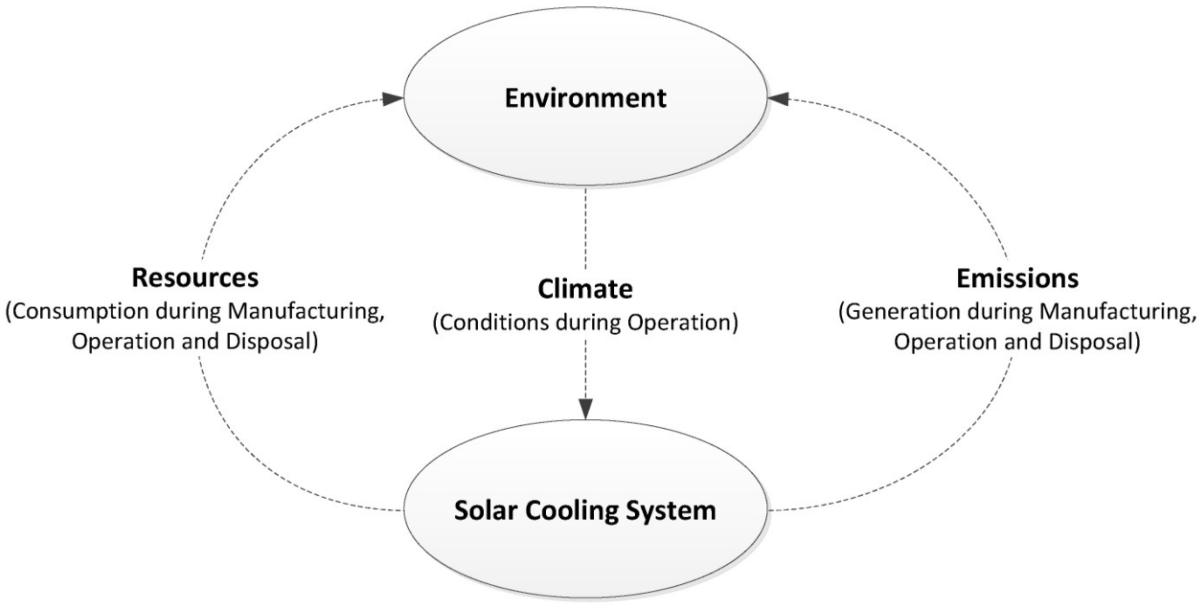


Figure 4-7: Interactions between the environment and a solar cooling system

The consumption of resources and the generation of emissions have an impact on the environment during the whole life cycle of a solar cooling system. From an environmental perspective, these impacts must be reduced to preserve its stable status. The climate represents a given, unchangeable surrounding condition for the operation of a solar cooling system.

Considering environmental aspects for the development of an optimized system means to reduce the consumption of resources and the generation of emissions as well as preparing system design for a low negative impact of climate conditions.

These identified environmental aspects are described via applying the heat flow model for analysing the operation of a solar cooling system. In Figure 4-8 the key impacts are illustrated.

Recall that climate conditions have an unchangeable impact on all aspects of the system model being considered. The intensity of solar irradiation directly influences the amount of heat generation via the solar thermal systems and the cooling demand resulting from solar energy being absorbed by the building or passing through translucent parts of the building envelope. Outside temperature and humidity influence the cooling load for conditioning the indoor climate, as well as the performance of outside mounted cooling towers for heat rejection.

The outside temperature also affects the efficiency of solar thermal plants by influencing the amount of heat losses during heat generation. In addition, the efficiency of fossil or biomass-fired components depends on outside temperature and humidity by representing conditions for the combustion air.

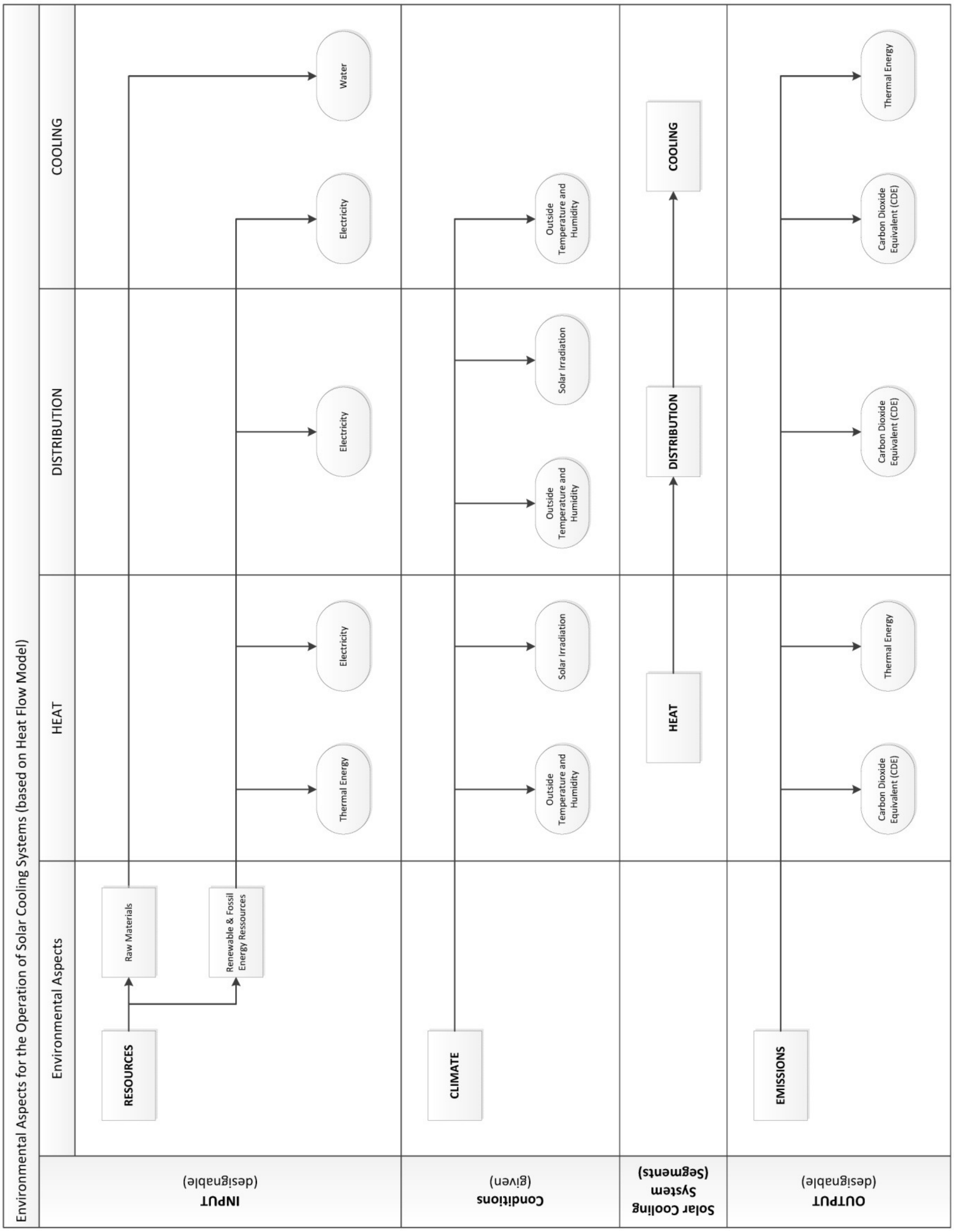


Figure 4-8: Environmental aspects during operation of a solar cooling system

The variation in solar irradiation, outside temperature and humidity around the globe is described via climate zones that lead to a differing impact on solar cooling systems depending on the installation location. This suggests that a geographically independent operation of a solar cooling system is necessary.

In Figure 4-8 the emissions during the operation of solar cooling systems are thermal energy and carbon dioxide equivalent (CDE). Declaring thermal energy as an emission derives from active routing of heat flows to the environment as it is represented by the overheat protection system of the solar thermal plant and by the heat rejection device of the sorption system. This may have a relevant impact on the environment, for example if the heat flow increases the temperature of ground or river water as occurs from heat rejection systems of electric power plants.

With a high global warming potential, the emission of CO_2 during operation mainly results from the generation of energy in its secondary forms heat and electricity. As heat for driving the sorption process is mainly generated by local technologies, the focus is on primary energy forms of decentralized heat generation. In Figure 4-9 the primary energy forms are classified to fossil and renewable energy sources.

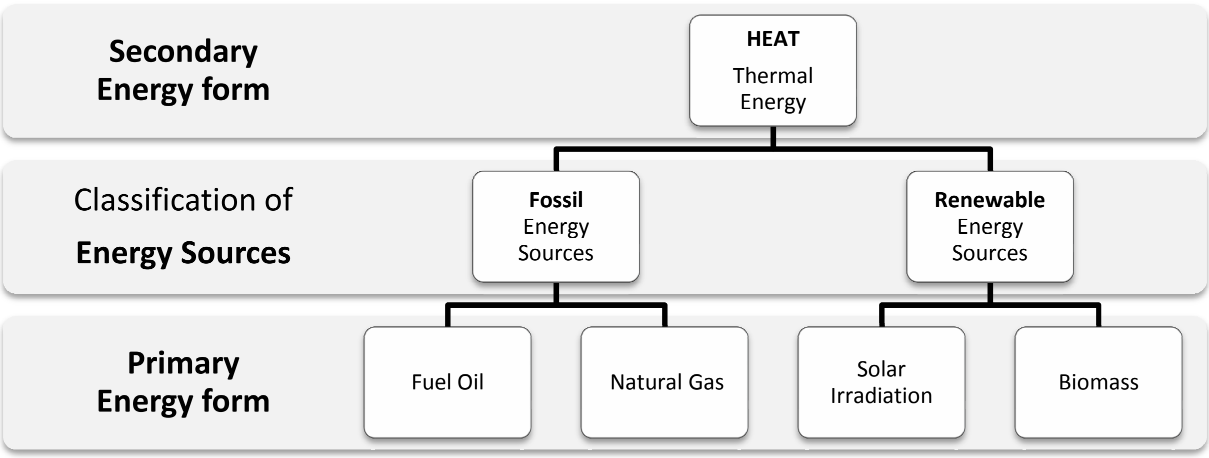


Figure 4-9: Classification of primary energy forms for decentralized heat generation

To reduce the production of CDE while operating the sorption process means to avoid fuel oil or natural gas for heat generation, and to favour solar irradiation and biomass. If fossil energy sources are necessary for e.g. back-up purposes, the heat generation process should be designed as efficient as possible. Even the consumption of raw materials such as using water for driving a wet cooling tower for heat rejection, should be reduced by efficient operation to save this resource.

Whereby heat is mainly provided via decentralised plants, the common principle for providing electricity consist of central power plants supplying a grid for distributing this energy form to the consumer. To operate a solar cooling system, electricity is needed for control and supplying actuators such as pumps, valves and fans. In addition to the classification of energy sources the primary energy forms to generate electricity are also classified by their basic energy form (see Figure 4-10).

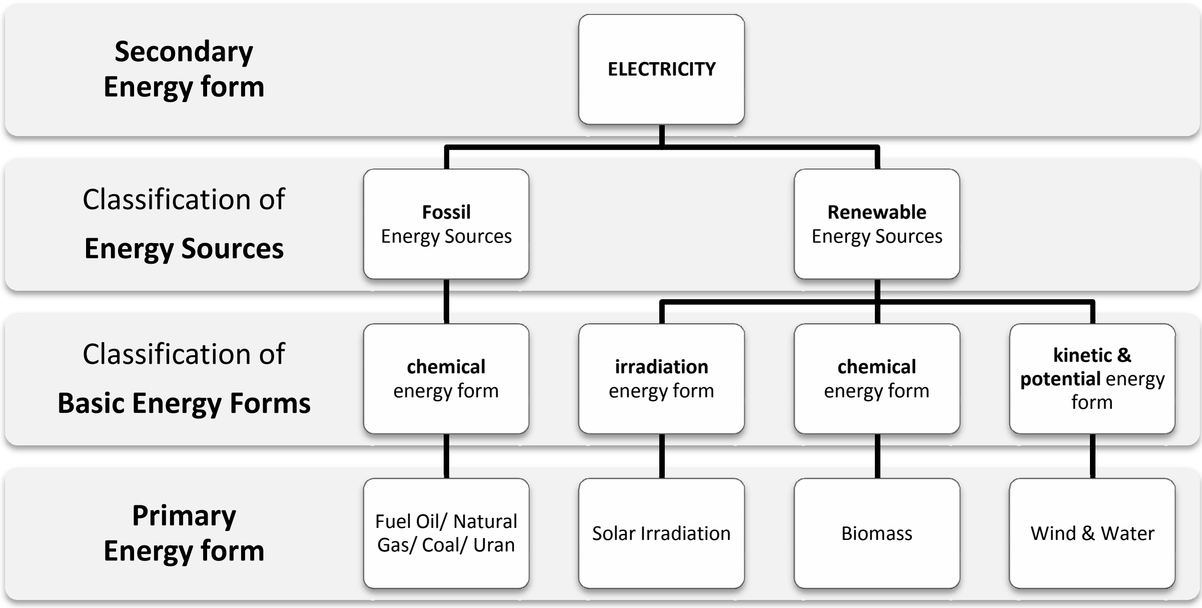


Figure 4-10: Classification of primary energy sources for the generation of electricity

While fossil energy sources consist of chemical energy forms, renewable energy sources include irradiative, kinetic and potential energy forms.

Regarding local, national and international principles for the generation of electricity, delivers a very high diversity. In contradiction to the generation of heat, the percentage of renewable energy sources for delivered electricity is given by the specific power plant scenario. To reduce the emission of CO_2 from electricity means to reduce the electric power consumption which can be described via an increase in the overall electrical COP of a solar cooling system.

To summarize designable and unchangeable conditions of the upper-level system “environment”, and to prepare for optimized system design, the relevant aspects are transferred to general environmental requirements (see Table 4-1). For every life cycle step, general attributes for reducing environmental impact by a solar cooling system and vice versa are defined.

Table 4-1: Environmental requirements for system design

Life Cycle Phase Of Solar Cooling System	General Environmental Requirements for System Design to • Reduce consumption of resources • Reduce emissions • Prepare for dynamic climate conditions
Manufacturing	• **Simplicity**
Operation	• **Efficiency** • **Priority for renewable energy sources** • **Variety** • **Reliability** • **Dynamic operation modes**
Disposal	• **Durability** • **Recyclability**

The general requirements for system design shown in Table 4-1, lead to reduced emissions, a lower consumption of resources and the preparation for dynamic climate conditions.

4.5.2 Market aspects

The focus within this section lies on correlations between the market and an integrated solar cooling system. Following the theory of nested systems, dependencies with this surrounding, upper-level system are analyzed while other dimensions are grayed out (see Figure 4-11).

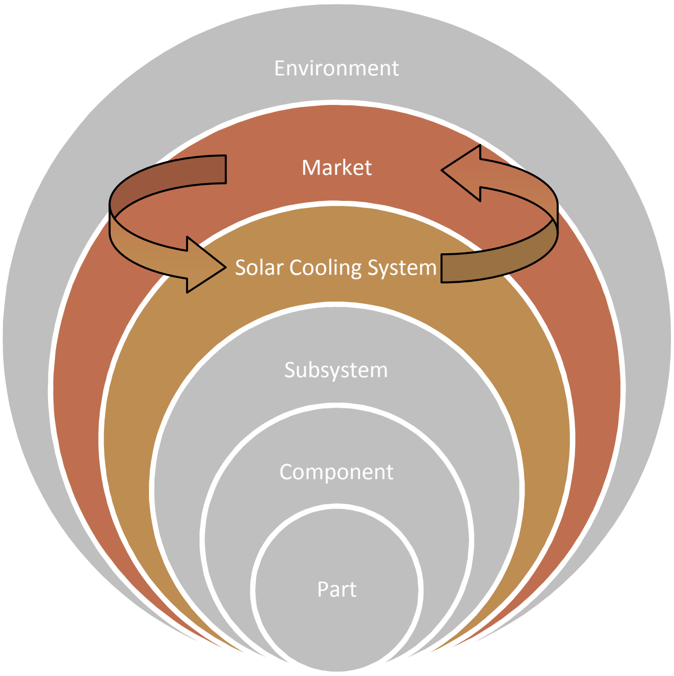


Figure 4-11: Model of nested systems – market & solar cooling system

The first step is to identify relevant markets. Those are markets which impact a solar cooling system during its life time cycle or vice versa. To achieve a marketing perspective, the heat flow model (HDC-model) of a solar cooling system is applied to identify the markets involved (see Figure 4-12).

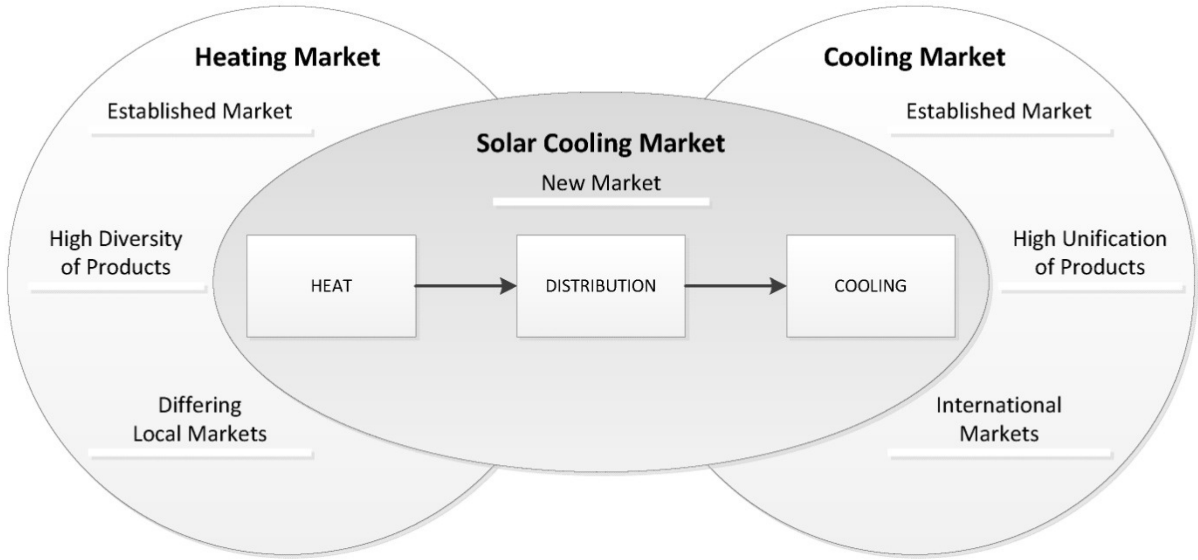


Figure 4-12: Markets identified via a solar cooling heat flow model

Considering the segments <u>H</u>EAT, <u>D</u>ISTRIBUTION and <u>C</u>OOLING, leads to the established heating market, the established cooling market and the new solar cooling market. Components and systems covered by the segment HEAT such as solar thermal systems can traditionally be found within the heating market. For example, heat rejection systems and sorption chillers of the segment COOLING are usually classified to be part of the cooling market. Considering the segment DISTRIBUTION leads to the heating and cooling market. Some of the components, such as fan coils are available on the cooling market, while other components such as storage tanks are part of the heating market. The established cooling market consists of an international market place with products of a high unification level. This aspect forces mass production and enables worldwide distribution networks. Analysing the established heating market delivers differing national and local markets with a high diversity of products. Implemented heating solutions are often highly depend on national preferences and on the educational level of local installers. Components for the heating market are distributed internationally, while systems consisting of these components are designed predominant locally. With the development of solar cooling systems, a new market with dependencies to existing markets was formed. On the one hand, the solar cooling market is a result of missing services offered from the established markets, and on the other hand new emerging characteristics of the product “solar cooling” require a different market place. The market development of the new solar cooling market is illustrated in Figure 4-13.

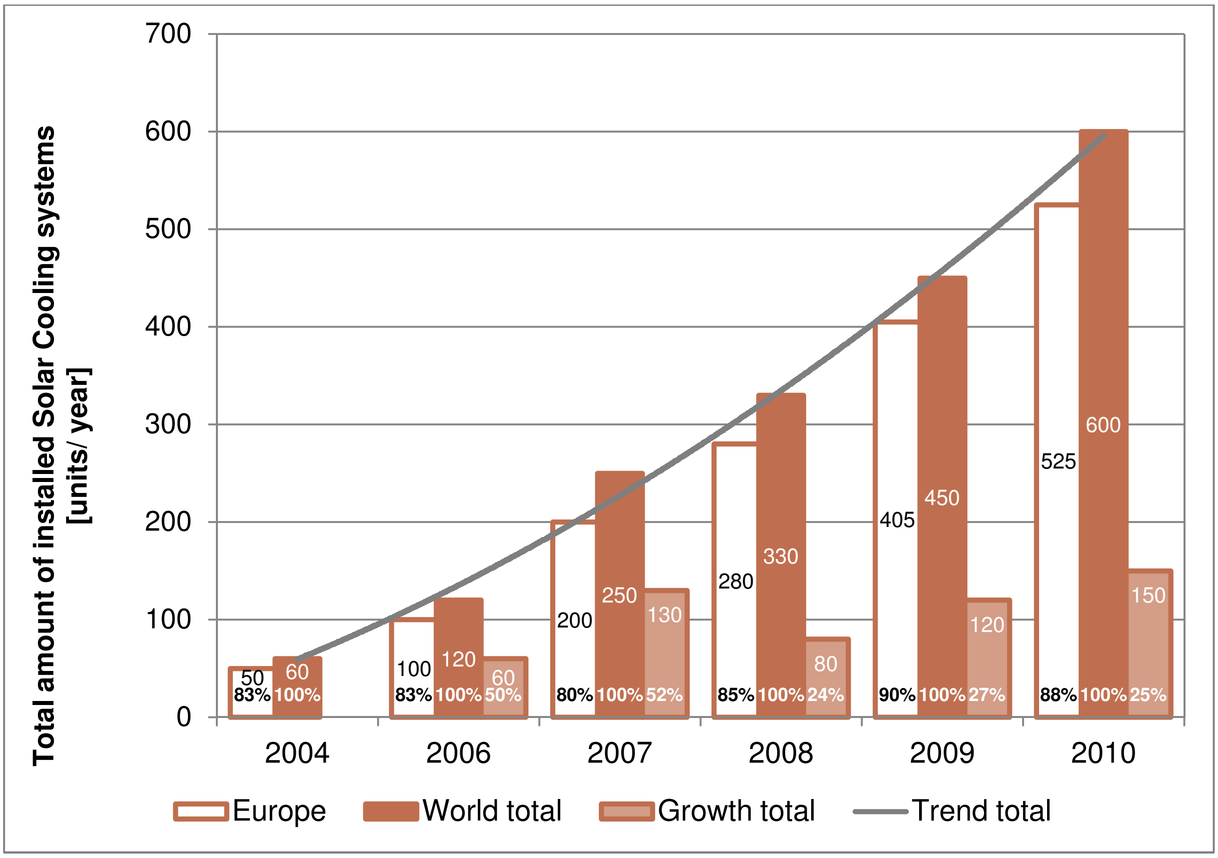


Figure 4-13: Solar cooling market development (Source of data: Solem Consulting 2011)

Until 2010 an estimated 600 plants were installed all around the world, of which 88% were in Europe. This niche market shows a continuing growth of minimum 24% per year. Both identified aspects - small size and strong growth – are typical for new markets. But in contradiction to established markets the attainable new market size is hard to estimate. This uncertainty represents one of the most influencing risks for market players.

The established cooling market, whose development is illustrated via sold conventional air-conditioning units in Figure 4-14, also shows a continuing growth during recent years. But in contradiction to solar cooling systems, a maximum of 10% are sold in Europe. The majority of conventional air-conditioning units are sold outside of Europe, for example in Asia and the USA. Regarding the amount of units sold per year, for example 77 million compared to 150 solar cooling systems in 2010, indicates the huge potential for green cooling technology.

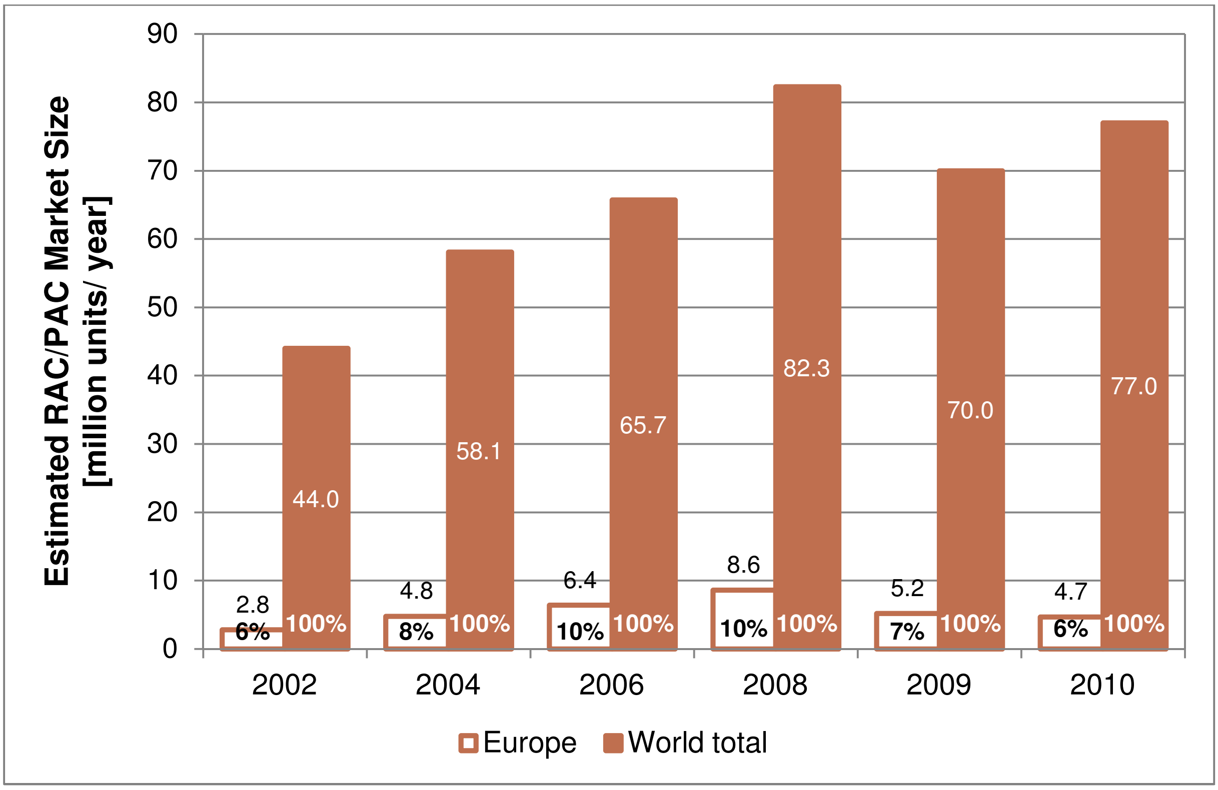


Figure 4-14: Cooling market development of conventional air-conditioning (Source of data: Solem Consulting / JARN, 2011)

Recall that possible solutions for "cooling" differ from those for "heating", leading to separate markets. A solar cooling system mainly consists of components from the heating market, and covers the demand of the cooling market. This leads to the presumption that solar cooling systems may be distributed within the existing heating market, delivering an additional benefit. But to provide an adequate product for this market, means to cover the heating demand as well. Following this strategy, and focusing on the cooling market shows that promising applications are those which, in addition to cooling purposes, require heating. This aspect represents one challenge for the new solar cooling market, combining solutions for heating and cooling. For more details, the involved markets are analysed towards their impact on a solar cooling system. Figure 4-15 illustrates identified dependencies between a solar cooling system, the heating market, the cooling market and the new solar cooling market.

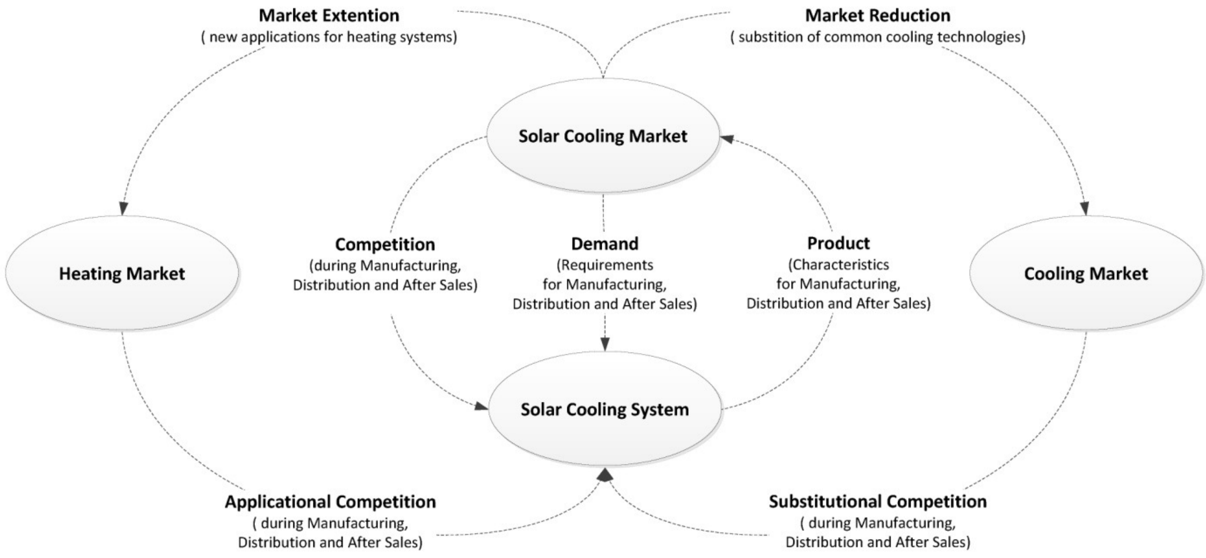


Figure 4-15: Correlations between involved Markets and a Solar Cooling System

The growth of a solar cooling market influences both established markets. For the heating market, solar cooling represents an additional sales potential by offering new applications for heating and cooling. By offering an alternative cooling solution, solar cooling systems substitute common cooling technologies offered on the cooling market. This means that the solar cooling market extends the heating market by reducing the cooling market. Cooling as a novel application for heating systems is on the one hand interesting for pioneers of the heating market, which may try to cover this field with traditional technology such as the heat pump. It is also important to consider whether an existing cooling market player has an interest in avoiding the substitution of common cooling technology.

From this perspective, both established markets are in competition with the product “solar cooling”. In addition to common competitors within the “home market”, a solar cooling system generates an application competition with the heating market, and a substitution competition with the cooling market. To resolve this challenge, the market positioning of solar cooling systems has to be included during system design.

Beside the given condition of competition, Figure 4-15 shows the market demand as another given aspect. The influence of demand is represented via specific requirements for heating and cooling solutions, raised by the stakeholders involved. Those on the one hand are suppliers represented by manufacturers and distributors, and on the other hand are buyers and users which generate the market demand. Successful products satisfy a good portion of needs raised by the stakeholders. The demand of manufacturers and distributors, illustrated in Figure 4-16, mainly consist of market-oriented and product-oriented aspects. A low competition, a high sales performance and a good market potential represent the market-influenced perspective. Costs from production, service and engineering are highly influenced by the distributed product. Combining good market-orientation with good product design leads to a high profit. And in general, the manufacturer or distributor has a high interest in respecting legal requirements and to receive sponsorship.

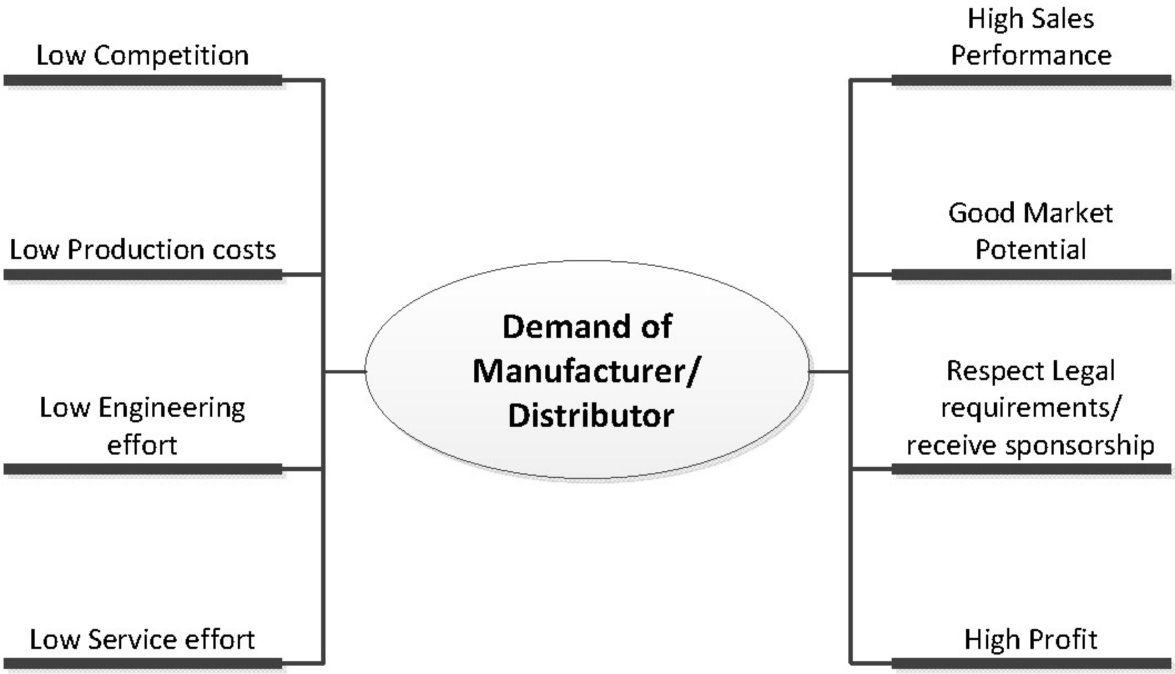


Figure 4-16: Demand of manufacturer and distributor of a solar cooling system

The demand raised by buyers and users shown in Figure 4-17 mainly consist of product-oriented aspects. A high durability, usability and reliability can be described with the product quality.

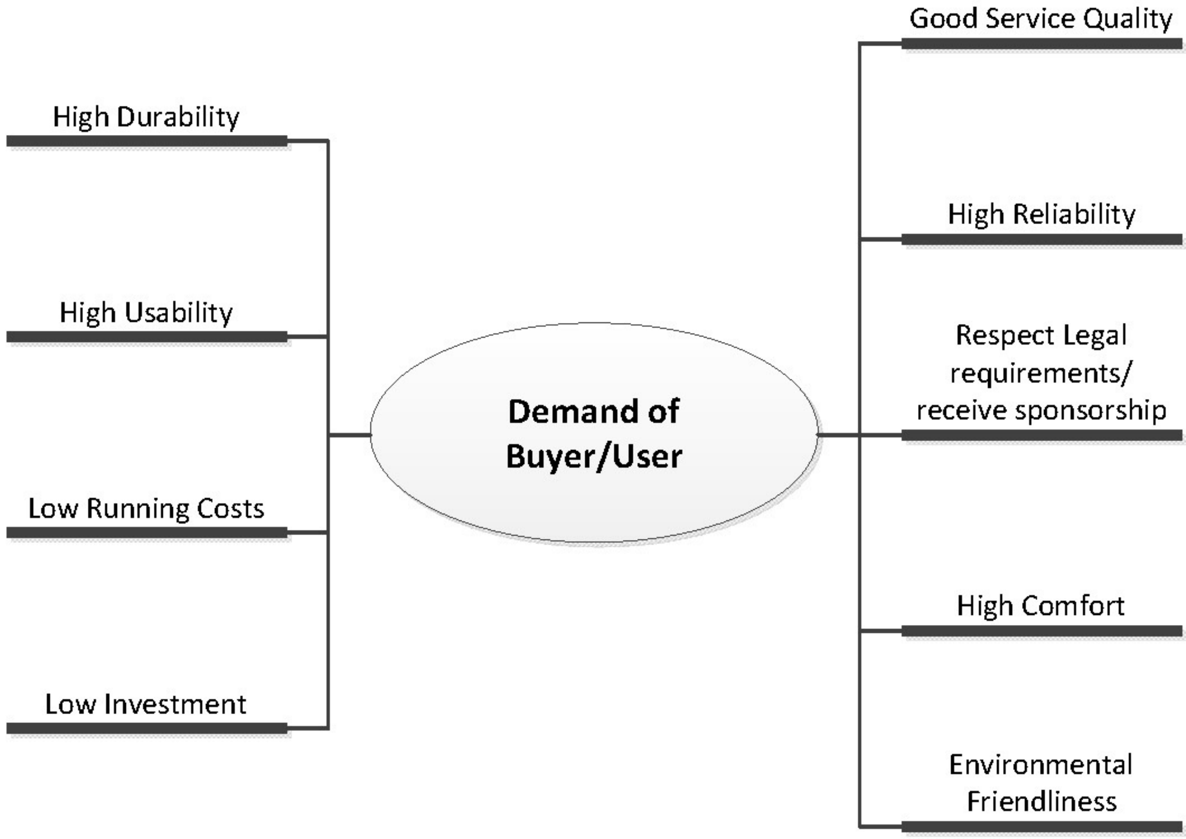


Figure 4-17: Demand of buyers and users of a solar cooling system

Monetary aspects are low running costs and a low capital investment. A good service quality given by the manufacturer and distributor influences the buying decision as well as general aspects such as good comfort and environmental friendliness. In accordance to the demand of manufacturers and distributors, the buyer and user has a high interest in respecting legal requirements and to receive sponsorship.

Recall that successful products satisfy a good portion of needs raised by the stakeholders involved. Summarizing the demand perspectives shows that most of the demand aspects raised by manufacturers and distributors are consistent with the demand aspects of buyers and users. For example does a good product quality (demand of buyer/user) lead to low service effort (demand of manufacturer/ distributor). Other aspects are in contradiction to each other, like the pursuit of high profit (demand of manufacturer/ distributor) on the one hand, and the demand for low investment (buyer/ user) on the other. It is all the more important that all interacting demand aspects are transferred to general requirements for system design to enable a highest possible grade of satisfaction for all stakeholders.

To summarize designable and unchangeable conditions of the upper-level system “market”, the relevant aspects are transferred to general market requirements (see Table 4-2). For every life cycle step, general attributes to enable market success are defined.

Table 4-2: Market requirements for system design

Marketing Life Cycle	General Market Requirements for System Design to • Satisfy demand • Develop product characteristics • Prepare for competition
Manufacturing	• **Low costs and investment** • **Simplicity**
Sales/ Operation/ Market volume	• **Low running costs →Efficiency** • **Reliability** • **Usability** • **Priority for renewable energy sources** • **Variety (location, application specific, etc.)** • **Dynamic operation modes (heating and cooling)**
Service/ After-Sales	• **Durability** • **Service friendliness** • **Recyclability**

The general requirements for system design shown in Table 4-2, help to satisfy demand, to develop product characteristics and to prepare for competition.

4.5.3 Synthesis of surrounding aspects via chains of correlations

Following the theory of nested systems, chains of correlations between the upper-level systems “Environment” and “Market” with a solar cooling system were considered to analyse emerging effects from combining general requirements (see Figure 4-18).

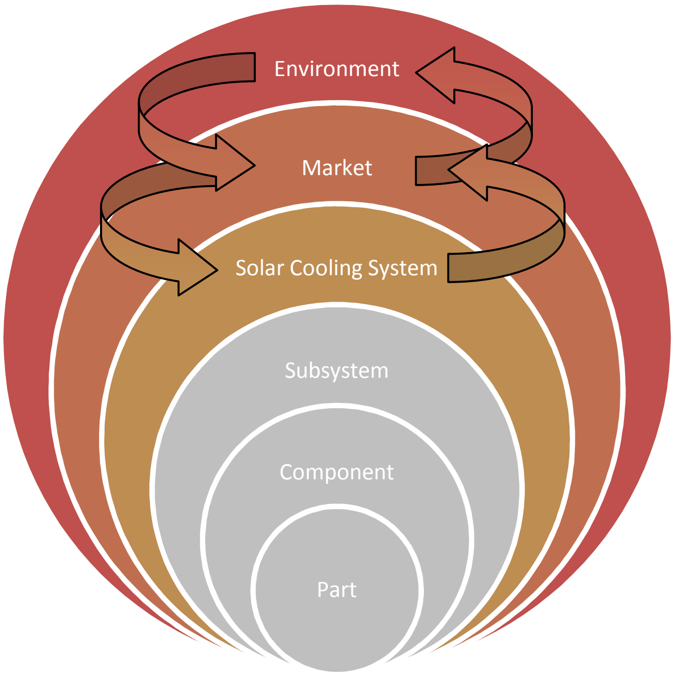


Figure 4-18: Model of nested systems – chains of correlations

Correlation chains are based on realistic cases which include elements of several model segments. These simple “case studies” are very helpful to check the already identified general requirements of each system to be consistent with each other. Correlation chains can easily be developed by questions concerning to several model segments. For this work, there must be clarification on how the environment influences markets for solar cooling systems and vice versa. Climate conditions for example, lead to the demand for cooling, heating or cooling & heating systems, resulting from differing geographical markets. The local deposit of fossil energy resources, raw material and existing infrastructure affects the running costs for driving conventional cooling systems, and therefore sets a benchmark for competition. These examples of chains make it clear that markets are highly variable in terms of environmental aspects. For an international distribution of solar cooling systems, the product must cover a variety of applications as required by geographical factors.

Proceeding in the other direction of the chain, leads to the question of how do solar cooling systems have an impact on geographical markets concerning to the environment. Different impacts on the environment appear, when e.g. considering the differing local deposit of fossil energy resources and existing infrastructure. Operating decentralized solar cooling systems, will in general reduce the emission of CDE firstly locally by substituting air-con units with climate harming refrigerants, and secondly regional and national by reducing the consumption of fossil energy resources. The specific environmental benefit will vary depending on each geographical market. By offering a variable system architecture, local components and subsystem can be integrated, which saves large transport efforts on the one hand, and delivers novel perspectives for the resident economy on the other. Moreover decentralized, high efficient and renewable technologies strengthen the energy supply guarantee.

Having proved the identified upper-level requirements against negative emerging effects, market and environmental requirements are combined to one "upper-level-system" (see Figure 4-19).

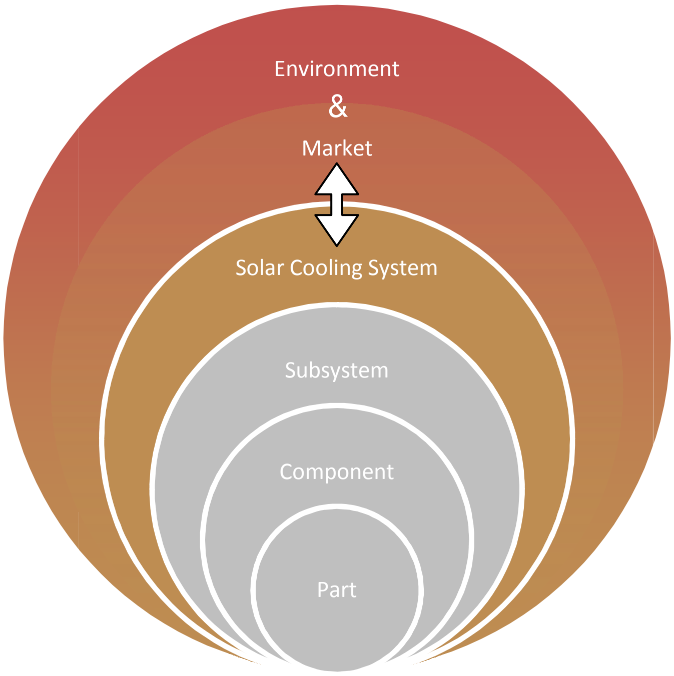


Figure 4-19: Model of nested systems – top-down requirements for system design

Through defining general requirements including environmental, marketing and combined perspectives, the specific upper-level aspects are transferred to the investigational level of solar cooling system design (see Table 4-3).

Table 4-3: Upper-level requirements for system design

Life & Marketing Cycle Solar Cooling System	General Upper-Level Requirements for System Design to • Reduce consumption of resources • Reduce emissions • Prepare for dynamic climate conditions • Satisfy demand • Develop product characteristics • Prepare for competition
Manufacturing	• **Low costs and investment** • **Simplicity of Manufacture**
Market volume/ Sales/ Operation / Distribution	• **Low running costs →Efficiency** • **Reliability** • **Usability** • **Priority for renewable energy sources** • **Variety & local components** • **Dynamic operation modes Cooling/ Heating & Cooling /Heating**
Disposal /Service/ After-Sales	• **Durability** • **Service friendliness & local training** • **Recyclability**

Recall that the theory of nested systems states that the combination of systems leads to emerging effects, which could be positive or negative.

To identify positive effects – so called synergies, a model of upper-level requirements for system design was developed (see Figure 4-20). The model consists of all general requirements being sorted to enable synergies. By illustrating correlations between the specific requirement aspects, direct and indirect achievable targets could be identified. The model shows that simplicity, variety, and efficiency could be a direct result of good system design (see yellow marked requirements in Figure 4-20). Other requirements as for example reliability, durability, low running costs and investment or service and environmental friendliness are a result of direct influence able aspects, and therefore are defined as being achievable indirectly (see red marked requirements in Figure 4-20).

Furthermore, the model illustrates the occurrence of positive emerging effects while combining requirements. For example, reliability, durability and efficiency all lead to low running costs. With a good combination of those possibilities, synergies will help to achieve a higher impact for the target “low running costs”.

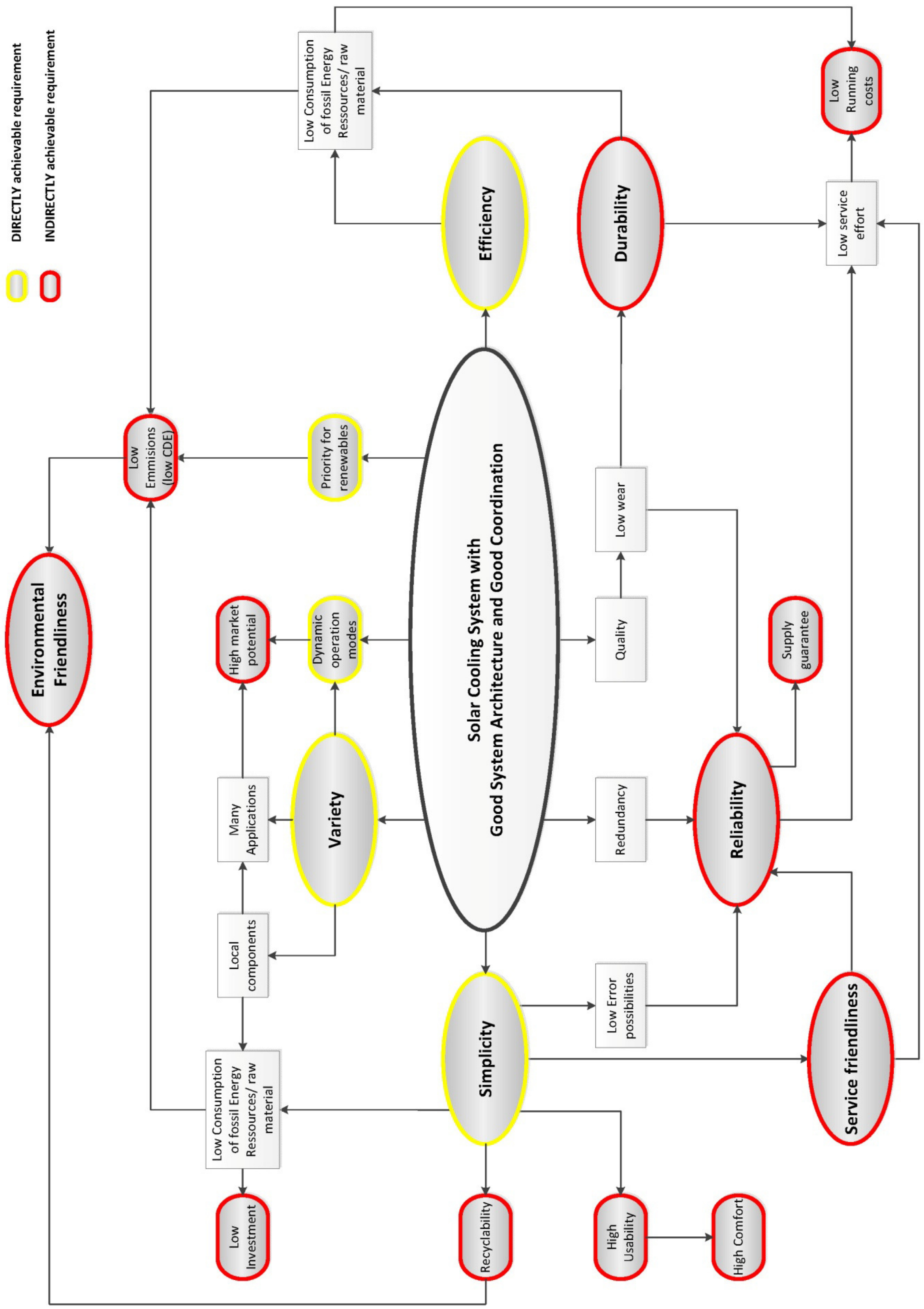


Figure 4-20: Model of upper-level requirements for system design

The model confirms the importance of system architecture, as requirements could be achieved by optimized solar cooling system design. Furthermore the model revealed the necessity of combining good architecture with good coordination while operating the system to achieve all requirements.

4.6 Functional analysis of system architecture via the GLD-method

This section focuses on analysing the coordination of a solar cooling system regarding the 2007 pilot plant. To identify the overall system coordination a novel method for analyzing operation modes of thermal systems was developed via abduction. The Generation-Link-Demand –method (GLD) delivers an abstract functional model by declaring all components of a thermal system to their role concerning the heat flow within the system. By regarding different operation modes, specific functional chains can be created to evaluate system design. These specific roles are Generation (G), Linking (L), Demand (D) and Sink (S). Depending on its heat flow interfaces, each component or subsystem has a minimum of one functional role concerning to its overall coordination. A component generating heat or cooling is declared as G (Generation). A storage system for example which just links the heat flow is declared as L (Link). Heating and cooling circuits, exchanging the heat or cooling load are D (Demand), and components which transport heat to the environment without covering demand are S (Sink). This method is based on the principle of cause and effect, and therefore illustrates the functional correlations within a solar cooling system. In Figure 4-21 the heat flow analysis applied to the 2007 pilot plant (HDC-modeling) is supplemented with the GLD-method.

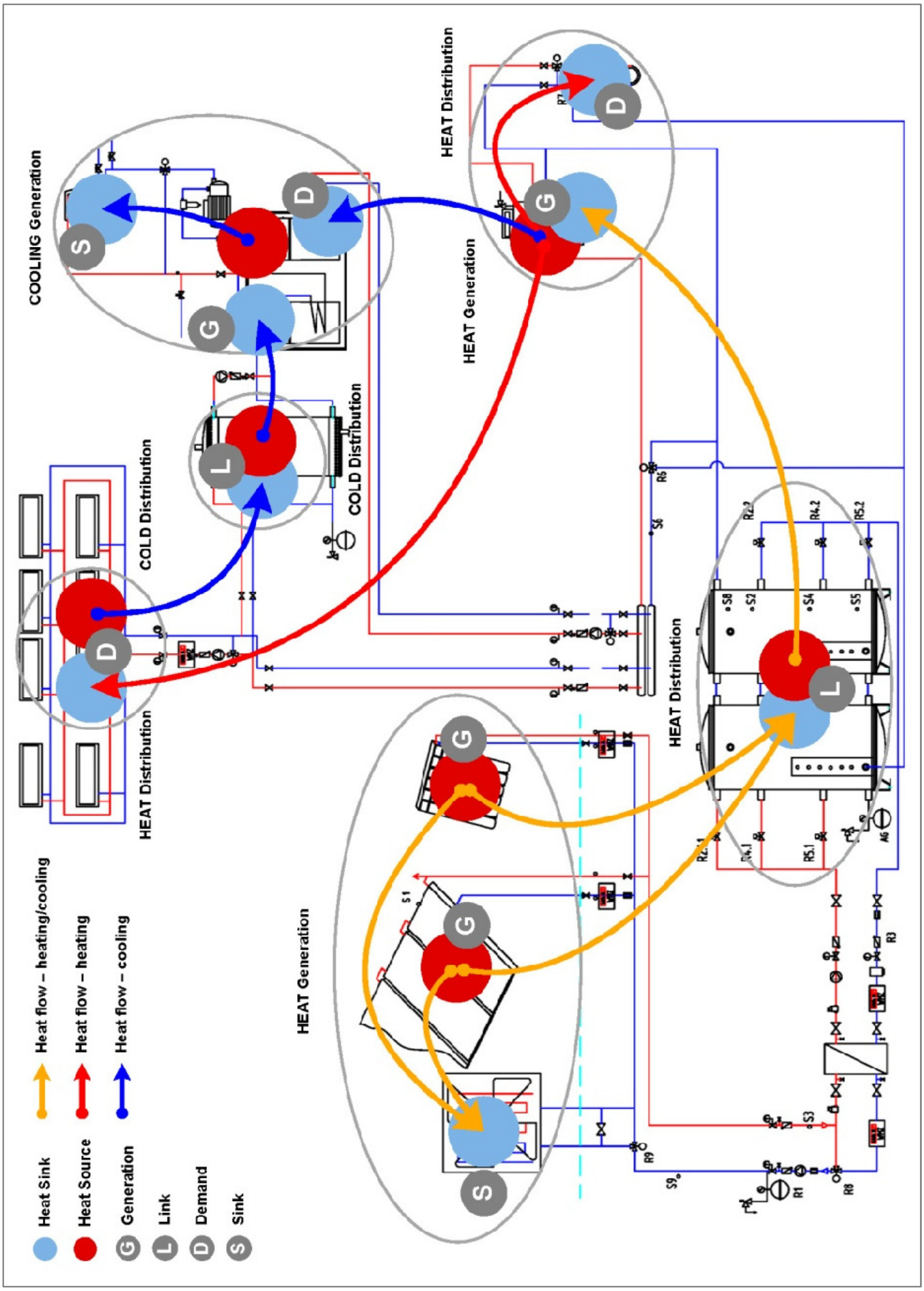


Figure 4-21: GLD-analysis of the 2007 pilot plant and classification to segments according to the heat flow model

The most simplest cause and effect chain consists of one demanding and one generating component, as for example a heating circuit (Demand), supplied with heat generated by an oil-fired boiler (Generation). In this case the cause and effect chain can be written as G-D. Solar thermal systems usually consist of collectors and a heat storage from which the heat is distributed to cover demand. Applying the GLD-method delivers: G-L-D. For evaluating system design, requirements for efficient and well coordinated thermal systems according to the GLD-method are defined:

1. **Closed chain for heat flow**
   Generation of thermal energy and linking to cover demand is enabled
2. **Minimization of elements involved**
   Heat flow is linked to demand by the shortest way considering the components characteristics
3. **Closed loops for information**
   Information can be transferred from demand to generation and vice versa
4. **Demand-oriented generation**
   Temperature and performance of provided thermal energy are caused by demand

The described GLD-method is used to evaluate the system architecture of the 2007 pilot plant with focus on the overall system coordination. In a first step, operation modes of the system are described. Secondly, the identified modes are analyzed and evaluated according to the defined requirements. The considered operation modes of the 2007 pilot plant are *A. Solar (assisted) Heating* and *B. Solar (assisted) Cooling*. The system architecture does not provide pure solar driven heating and cooling because of the hydraulic implementation of the fossil driven boiler. Therefore both modes are solar-assisted.

A. Solar (-assisted) Heating (G-L-G-D):

Heat generation via solar collectors (G) → charging and discharging heat storage (L) → heat flow through oil-fired boiler and in case of insufficient temperature generation of heat (G) → distribution of heat via heating circuit and covering heat demand of the building via radiators, fan coils and heated ceilings (D)

B. Solar (-assisted) Cooling (G-L-G-D-S) and (D-L-G-S):

Heat generation via solar collectors (G) → charging and discharging heat storage (L) → heat flow through oil-fired boiler and in case of insufficient temperature generation of heat (G) → covering heat demand of the sorption chiller (D) → transfer of heat to the environment via the wet cooling tower (S) ← cold generation via sorption process (G) ← charging and discharging cold storage (L) ← distribution of cooled fluid via cooling circuit and covering cooling demand of the building via fan coils and cooled ceilings (D). In Table 4–4, the identified operation modes (A and B) are compared with the defined benchmarks for optimized system design.

Table 4-4: Evaluation of operation modes via GLD-method

Requirement (for optimized thermal systems according to the GLD-method)	**A. Solar (-assisted) Heating** **G-L-G-D** (Operation mode of the 2007 pilot plant)	**B. Solar (-assisted) Cooling** **G-L-G-D-S and D-L-G-S** (Operation mode of the 2007 pilot plant)
1. Closed chain for heat flow	☑ **YES**	☑ **YES**
2. Minimization of elements involved	☒ **NO** Shortest linking of heat flow considering the solar thermal system would be: **G-L-D**	☒ **NO** Shortest linking of supply heat flow considering the solar thermal system would be: **G-L-D-S and –D-L-G-S**
3. Closed loop for information	☒ **NO** No closed overall loop – 3 separate and overlapping information loops: **(G-L)** Solar heat generation and charging of heat storage **(L-D)** discharging heat storage via 3-way-valve to heating circuits **(G-D)** heat flow through oil-fired boiler and in case of insufficient temperature generation of heat	☒ **NO** No closed overall loop – 4 separate and overlapping information loops: **(G-L)** Solar heat generation and charging of heat storage **(L-D)** discharging heat storage via 3-way-valve to heating circuits **(G-D-S)** heat flow through oil-fired boiler and in case of insufficient temperature generation of heat, heat supply of sorption chiller and transfer to the environment via heat rejection **(D-L-G-S)** distribution of cooled fluid via cooling circuit; charging and discharging cold storage, cold generation via sorption process, transfer of heat to the environment via wet cooling tower
4. Demand-oriented generation	☒ **NO** Temperature and performance of supplied solar thermal heat not caused by heating demand	☒ **NO** Temperature and performance of supplied solar thermal/ fossil generated heat/ cold generation by sorption chiller - not caused by heating/ cooling demand.

The evaluation of operation modes illustrates that only 1 of 4 characteristics for system architecture with good coordination is given by the 2007 solar cooling system (see Table 4–4). *A closed chain for heat flow* ((1) in Table 4–4) given by the hydraulic connections is the minimum requirement for a thermal system to enable the coverage of demand. *The number of elements involved during operation* ((2) in Table 4–4) affects overall efficiency and speed of the system. *A closed loop for information* ((3) in Table 4–4) is a basic requirement for good coordination. With the grade of *demand-oriented generation* ((4) in Table 4–4), those two characteristics strongly influence the systems reliability and efficiency. Within the following sections the identified shortcomings are regarded in detail by analyzing subsystems, components and their functional correlations with system architecture.

4.7 Analysis of subsystems

With the analysis of subsystems the first lower-level system according to the theory of nested systems applied for solar cooling is considered (see Figure 4-22). The focus within this section lies on integrated subsystems and their interfaces for the overall coordination of a solar cooling system.

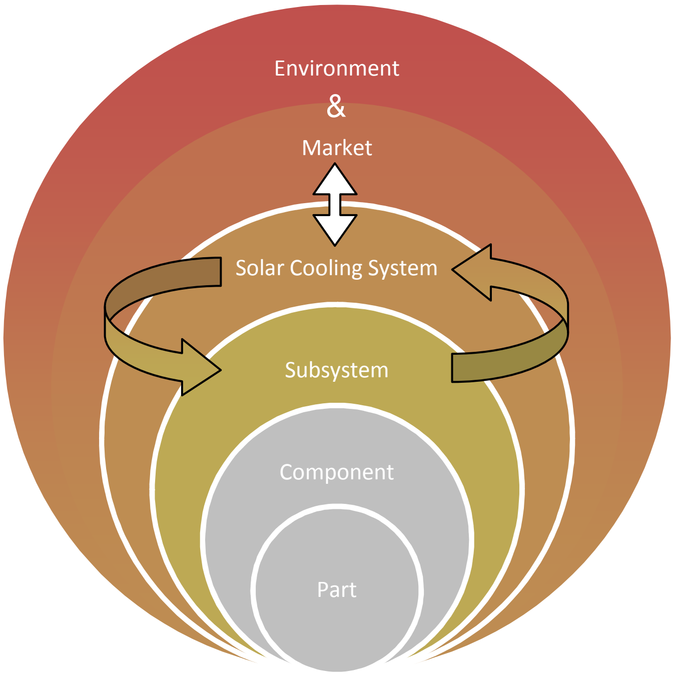


Figure 4-22: Model of Nested systems – Subsystems & Solar Cooling system with Top-Down requirements

For identifying existing subsystems, firstly the meaning of “subsystems” in the context of a solar thermally driven sorption system needs to be clarified. Here, subsystems are defined as a group of components which are usually operated as stand-alone-systems, or which are implemented as such, or could be regarded as independent systems with interfaces to others. Regarding the 2007 pilot plant, the installation of several controllers delivers a solar cooling system consisting of four subsystems, which are the solar thermal system ((**1**) in Figure 4-23), the oil-fired boiler with direct connected heating circuit ((**2**) in Figure 4-23), the sorption system ((**3**) in Figure 4-23) and the combined heating and cooling circuit ((**4**) in Figure 4-23).

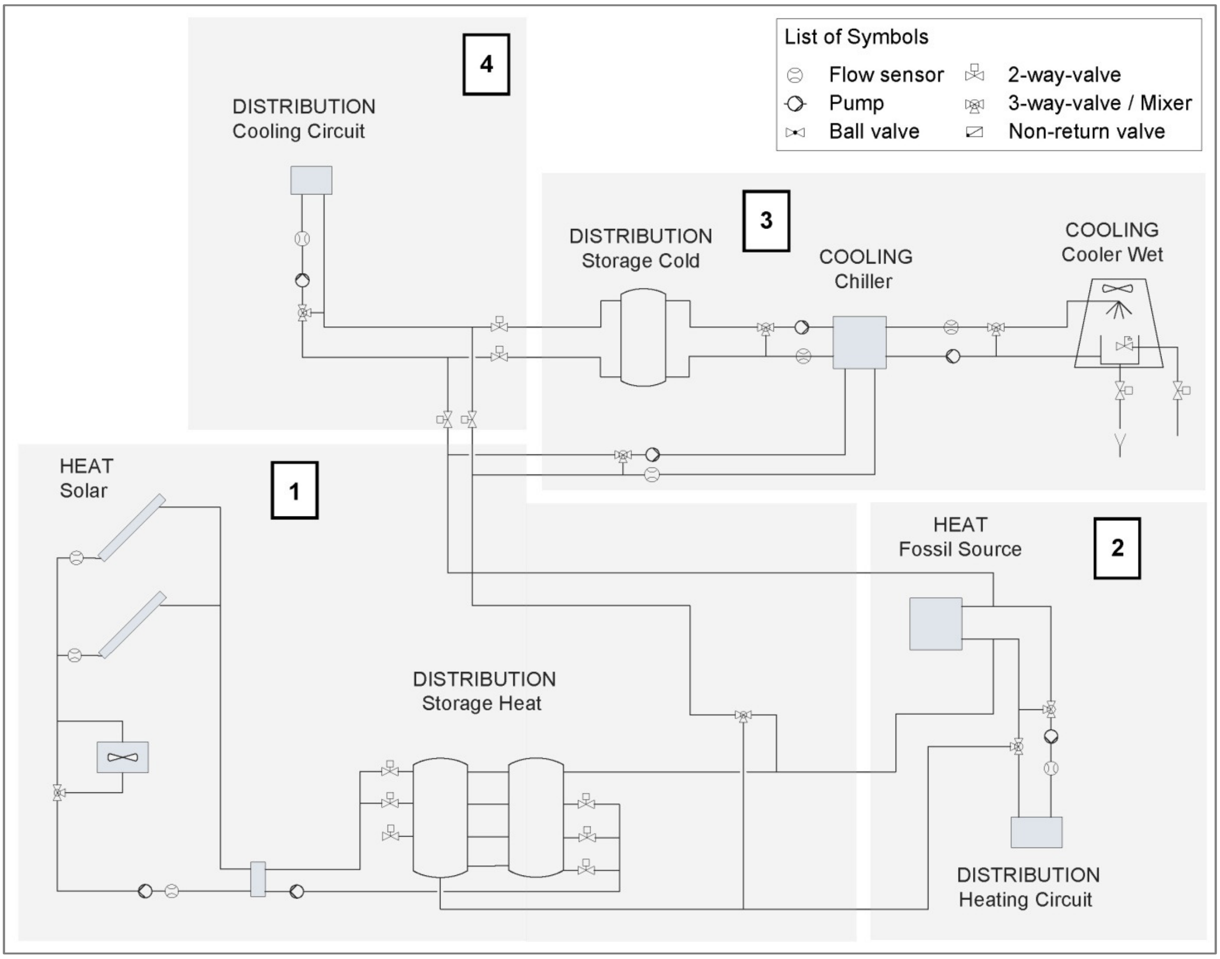


Figure 4-23: Subsystems of the 2007 pilot plant

Recall that 3 of 4 characteristics for system architecture with good coordination could not be given by the 2007 solar cooling system (see Table 4–4 in section 4.6). For identifying causes of those shortcomings, each subsystem is analyzed in detail.

Firstly, the coordination is evaluated via the GLD-method. Secondly, impacts on other subsystems are analyzed. Thirdly, the compliance with applicable upper-level requirements for good system design is considered (see Table 4-3).

4.7.1 Solar thermal subsystem

The solar thermal system consists of flat-plate collectors and vacuum tubes for heat generation, and a storage system with components for charging and discharging. As an active overheating protection, an air-fluid heat exchanger is installed outside to transport solar surplus to the environment. For heat supply, the solar thermal generated heat is distributed via a return-flow boost of the oil-fired boiler. For analysing subsystems, the GLD-method is detailed via additional hydraulic and control aspects (see Table 4-5).

Table 4-5: Evaluation of solar thermal Subsystem via GLD-method

Requirements (for optimized thermal systems according to the GLD-method)		**Solar thermal Subsystem** **(G-L) (G-S) (L-G-D)** Operation modes of the 2007 pilot plant: **A. Solar-assisted Heating** **B. Solar-assisted Cooling**
1. Closed chain for heat flow	**a) Hydraulics**	☑ **YES**
2. Minimization of elements involved	**a) Number of Components for heat flow**	☑ **YES** Shortest linking of heat flow **(G-L)** Solar heat generation and charging of heat storage **(G-S)** Linking solar thermal surplus to the environment via air-fluid heat exchanger ☒ **NO** Linking of heat flow making a detour via oil-fired boiler **(L-G-D)** discharging heat storage via 3-way-valve to oil-fired boiler and then to heating circuits
	b) Number of Hydraulic elements	☒ **NO** 2 pumps, one plate heat exchanger, 9 valves,
	c) Number of Control elements	☒ **NO** One Solar Controller Sensors: 10 Temperature sensors Actuators: 2 pumps, 9 electrical drives
3. Closed loop for information	**a) Heating mode** **b) Cooling mode**	☒ **NO** No closed overall loop – 2 separate and overlapping information loops: **(G-L)** Solar heat generation and charging of heat storage **(L-G-D)** discharging heat storage via 3-way-valve to the heating circuits and to the sorption chiller
4. Demand-oriented generation	**a) Demand-oriented temperature**	☒ **NO** Temperature difference control doesn't deliver temperature caused by heating/ cooling demand.

The high number of hydraulic and control elements involved (see Table 4-5) raise the consumption of electric energy caused by higher pressure drops and stand-by losses. Furthermore, a higher number of elements lead to more complexity and consumption of raw material, which negatively affects investment, running costs and environmental impact.

During operation, the weak points of the solar thermal subsystem also have negative impact on other subsystems. The open information loop ((3) in Table 4-5) and the control strategy ((4) in Table 4-5) lead to an inefficient operation of the oil-fired boiler system, causes a late start-up for cold production by the sorption system and does not enable priority for renewable generated heat. For providing sufficient temperature for operating the sorption chiller, the oil-fired boiler is in permanent standby-mode, which leads to unnecessary heat losses. To ensure sufficient operation conditions for the sorption chiller subsystem, the start-up signal depends on the temperature of the heat storage. With temperature difference control of the solar thermal system, a sufficient temperature is reached when the whole storage volume was heated up. Therefore, the solar thermal subsystem causes a late start-up of cold production, even on sunny days. Furthermore, by not considering the required temperature, the solar thermal generated heat has to be permanently heated-up by the oil-fired boiler to provide heating demand, even for the heating circuits.

For high solar gains in general, temperature difference control is a proven and high efficient method. However, by emerging effects through combining subsystems, this control strategy causes inefficient operation of other subsystems and does not enable priority for renewable generated heat.

4.7.2 Oil-fired boiler subsystem

This subsystem consists of an oil-fired boiler with a direct connected heating circuit. The heating circuit distributes heat via fluid flow to the convectors, which are installed within all rooms of the office building. This subsystem already existed before implementing the solar cooling pilot plant to cover the heating demand of the building. Table 4-6 illustrates the results of the GLD-method applied to the oil-fired boiler subsystem.

Table 4-6: Evaluation of oil-fired boiler subsystem via GLD-method

Requirements (for optimized thermal systems according to the GLD-method)		**Oil-fired boiler Subsystem (G- D)** Operation modes of the 2007 pilot plant: **A. Solar-assisted Heating** **B. Solar-assisted Cooling**
1. Closed chain for heat flow	**a) Hydraulics**	☑ **YES** **(3x G-D)** Closed chains for supplying heating circuits (convectors and fancoils) and sorption chiller
2. Minimization of elements involved	**a) Number of Components for heat flow**	☑ **YES** Shortest linking of heat flow **(G-D)** fossil heat generation and supply of heating circuits and sorption chiller
	b) Number of Hydraulic elements	☑ **YES** 1 pump and 1 mixing valve of the heating circuit with convectors
	c) Number of Control elements	☑ **YES** One onboard-Controller Sensors: 2 Temperature sensors Actuators: 1 pump ,1 electrical drive
3. Closed loop for information	**a) Heating mode (convectors)**	☑ **YES** Closed information loop: **(G-D)** heat flow through oil-fired boiler and in case of insufficient temperature **automatically** generation of heat to supply the heating circuit with convectors
	b) Heating mode (fan coils)	☒ **NO** Open loop for information: **(G)** heat flow through oil-fired boiler and in case of insufficient temperature **manually** generation of heat to supply the heating circuit with fan coils (subsystem combined heating and cooling circuit)
	c) Cooling mode	☒ **NO** Open loop for information: **(G)** heat flow through oil-fired boiler and in case of insufficient temperature **manually** generation of heat to supply the sorption chiller subsystem

4. Demand-oriented generation	**a)**	Demand-oriented temperature **Heating mode (convectors)**	☑ **YES** **(G-D)** Outside temperature guided heat supply delivers temperature caused by heating demand.
	b)	Demand-oriented temperature **Heating mode (fan coils)**	☒ **NO** **(G)** Heat supply temperature is not caused by heating demand. Provided temperature is equal to the supply temperature of the heating circuit with convectors- if active. In case of insufficient temperature - switch to manual mode for a static temperature set point.
	c)	Demand-oriented temperature **Cooling mode**	☒ **NO** **(G)** Heat supply temperature is not caused by heat demand of the sorption chiller to cover the cooling demand. In case of insufficient temperature - switch to manual mode for a static temperature set point

Rating this subsystem via the GLD-method delivers an optimized stand-alone heating system with a minimum of elements involved, a closed loop for communicating demand and a demand-oriented heat supply for the heating circuit with convectors (see *1., 2., 3.a)* and *4.a)* in Table 4-6). But combining with other components to a solar cooling system, leads to additional supply tasks for this subsystem. Beneath the already existing heating circuit, the oil-fired boiler is used for providing the heat demand of the combined heating and cooling subsystem as well as for supplying the sorption chiller subsystem. Within the overall solar cooling system, the oil-fired boiler subsystem does not comply with tasks for good system architecture and good coordination resulting from the additional heat consumers (heating circuit fan coils and heat supply for sorption chiller). The outside temperature guided control strategy is only provided for the direct connected heating circuit with convectors. In case of heating mode, the combined heating and cooling circuit subsystem can only be supplied if the direct connected heating circuit is active. In this case, only a heat supply temperature that fits to convectors can be provided. For a sufficient temperature for distributing heat via fan coils, the control system has to be switched to manual mode for adjusting a static temperature set point. However, his leads to a degradation of the subsystems operation because of disabling the outside temperature guided control for the heating circuit with convectors on the one hand, and additional heat losses by permanent standby-mode of the oil-fired boiler on the other. Regarding the subsystems cooling mode, the manual mode with static temperature set point is the only possibility to provide a sufficient heat supply for the sorption chiller. There is no closed information loop and no demand oriented heat generation (see 3.c) and 4.c) in Table 4-6). As the subsystems are not connected for communication, the heating demand of the sorption chiller is not automatically covered by the oil-fired boiler system all the time. The heating-up of solar thermal generated energy is only enabled if the sorption chiller system detects sufficient heat within the storage tank, and therefore starts its heat supply pump. Another alternative for enabling a fluid flow from the oil-fired boiler to the sorption chiller is not enabled by the system. By not detecting the heating demand for cold generation, the oil-fired boiler system has a negative impact on the reliability of covering cooling demand by the sorption chiller subsystem and the combined heating and cooling circuit subsystem. The identified shortcomings result from open information loops and no demand orientation of heat generation by the oil-fired boiler system. Furthermore, the combination of a non-coordinated solar thermal subsystem with an optimized stand-alone oil-fired boiler subsystem worsens the reliability and efficiency of the overall solar cooling system.

4.7.3 Sorption chiller subsystem

The sorption chiller subsystem consists of a cold storage tank, a sorption chiller and a wet cooling tower for heat rejection. Via the sorption chiller, the cooling load of the cold storage is transferred to the wet cooling tower, releasing heat to the environment. To drive the sorption process, the chiller is supplied with heat from the hot storage tank and the oil-fired boiler. The results of rating the sorption chiller subsystem are shown in Table 4–7.

Table 4-7: Evaluation of sorption chiller subsystem via GLD-method

Requirements (for optimized thermal systems according to the GLD-method)		**Sorption chiller Subsystem (D-L-G-S) (D-S)** Operation modes of the 2007 pilot plant: **A. Solar-assisted Heating** **B. Solar-assisted Cooling**
1. Closed chain for heat flow	**a) Hydraulics**	☑ **YES**
2. Minimization of elements involved	**a) Number of Components for heat flow**	☑ **YES** Shortest linking of heat flow **(D-L-G-S)** Cooling load of the building is linked to the cold storage tank and transferred to the environment via sorption chiller and wet cooling tower **(D-S)** Heat to drive the chiller is transferred to the environment via chiller and wet cooling tower
	b) Number of Hydraulic elements	☑ **YES** 3 pumps, 4 valves,
	c) Number of Control elements	☒ **NO** One onboard Controller Sensors: 2 Temperature sensors Actuators: 3 pumps, 4 electrical drives, 1 vacuum pump
3. Closed loop for information	**a) Heat supply for sorption chiller**	☒ **NO** No closed loop for information: **(D)** Heating demand for driving the sorption chiller is not communicated to Heat generation units
	b) Cold generation	☑ **YES** Closed information loop: **(D-L-G)** Cooling demand of cooling circuit is covered via cold generation of sorption chiller charging the cold storage
4. Demand-oriented generation	**a) Demand-oriented heat supply for sorption chiller**	☒ **NO** **(D)** Demand for heat is not communicated to the heat generation units
	b) Demand-oriented cold generation	☑ **YES** **(D-L-G)** Cooling demand is caused by cooling circuit and covered by cold generation via the sorption chiller

The analysis via the GLD-method highlights the weakness of this subsystem concerning the heat supply for the sorption chiller (see *3.a)* and *4.a)* in Table 4–7). Resulting from an open information loop between heating demand for driving the sorption process and heat generation units, this subsystem is not able to cover a cooling load if demanded without a sufficient heat supply from the hot storage tank. This fact has an additional impact on the combined heating and cooling circuit subsystem, which therefore is not permanently enabled to distribute cold fluid to the fan coils and cooled ceilings.

4.7.4 Combined heating and cooling circuit subsystem

The combined heating and cooling circuit subsystem consists of fan coils and cooled ceilings within the building, a distribution pump and valves to switch the hydraulic connectivity between the cold and hot storage tanks. Evaluating the combined heating and cooling subsystem delivers results shown in Table 4-8.

Table 4-8: Evaluation of combined heating and cooling circuit subsystem via GLD-method

Requirements (for optimized thermal systems according to the GLD-method)		**Combined heating and cooling circuit Subsystem** **(L-D) (D-L-G)** Operation modes of the 2007 pilot plant: **C. Solar-assisted Heating** **A. Solar-assisted Cooling**
1. Closed chain for heat flow	**a) Hydraulics**	☑ **YES**
2. Minimization of elements involved	**a) Number of Components for heat flow**	☑ **YES** Shortest linking of heat flow **(L-D) Heating Mode** Heat from the hot storage is linked to the heating circuit **(D-L) Cooling Mode** Cooling load of the building is linked to the cold storage tank
	b) Number of Hydraulic elements	☒ **NO** 1 pump, 5 valves,
	c) Number of Control elements	☒ **NO** One Controller Sensors: 4 Temperature sensors Actuators: 1 pump, 5 electrical drives
3. Closed loop for information	**a) Heating mode**	☒ **NO** No closed loop for information: **(D)** Heating demand to supply the heating circuit is not communicated to Heat generation units
	b) Cooling mode	☑ **YES** Closed information loop: **(D-L-G)** Cooling Demand of cooling circuit is transferred to the sorption chiller control
4. Demand-oriented generation	**a) Demand-oriented heat supply for heating circuit**	☒ **NO** **(D)** Demand for heat is not communicated to the heat generation units
	b) Demand-oriented cold supply for cooling circuit	☑ **YES** **(D-L-G)** Cooling demand is caused by cooling circuit and covered by cold generation via the sorption chiller

The analysis of the combined heating and cooling subsystem via the GLD-method confirms the weak reliability of covering heating and cooling loads. The missing communication between heat demand and heat generation is the cause for this shortcoming of the 2007 pilot plant.

4.7.5 Coordination of subsystems and compliance with upper-level requirements

Recall that three of the four characteristics for system architecture with good coordination could not be given by the 2007 solar cooling system (see Table 4–4 in section 4.6). A good coordination of separated systems is based on sufficient transfer of information via adequate interfaces. Interfaces of thermal subsystems are connections between to transport information and/ or energy – implemented via hydraulics and control.

The subsystems are hydraulically connected to enable the heat transfer via fluid flow, but the combination of subsystems (see Table 4–4 in section 4.6) did not lead to a minimization of elements involved. For communication, only one control interface between subsystems was identified, signalling cooling demand of the combined heating and cooling circuit via one dry contact to the sorption chiller system. All other subsystems have stand-alone control without interfaces. Even though the combination of subsystems is able to cover demand, information for good coordination is not communicated. All subsystems are focused on their specific operation based on being provided by others - the overall control is missing.

These facts show that a missing overall system perspective enables negative emerging effects even if optimized subsystems are used for system design. Furthermore, the combination of subsystems leads to a strengthening of specific weakness to an even greater disadvantage for the overall system.

Considering applicable direct achievable requirements for good system architecture (see Figure 4-20), delivers a low compliance. The reliability and efficiency are poor, complexity is too high, dynamic operation modes are limited and the priority for renewables is missing (see Table 4-9).

Table 4-9: Compliance with applicable direct achievable upper-level requirements for system design

Direct achievable **Upper-Level Requirements** (via good System Design)	**Subsystems** of the 2007 pilot plant (Evaluation of Architecture and Coordination)
Simplicity	☒ **NO** Complex system with a low usability and a high number of elements involved → leads to poor reliability
Reliability	☒ **POOR** Poor reliability because of no overall coordination and no redundancy
Efficiency	☒ **POOR** Poor overall efficiency caused by combination of subsystems
Priority for renewables	☒ **NO** No priority for renewables resulting from a missing overall system perspective for system design
Dynamic operation modes	☒ **LIMITED** Limited operation modes because of poor coordination

As a result, from analysing subsystems, the necessity for overall system coordination could be shown - missing communication combined with insufficient system architecture led to a poor coordination even if optimized subsystems are combined. Furthermore, the application of the GLD-method delivered helpful details for good system architecture with good coordination. The proven requirements illustrated in Table 4-10, will be considered for optimized system design.

Table 4-10: Requirements for optimized thermal system design according to the GLD-method

Requirements (for optimized thermal systems according to the GLD-method)	
1. Closed chain for heat flow	Generation of thermal energy and linking to covering the demand is enabled
2. Minimization of elements involved	Heat flow is linked to demand the shortest way considering the components characteristics
3. Closed loops for information	Information can be transferred from demand to generation and vice versa
4. Demand-oriented generation	Temperature and performance of provided thermal energy are caused by demand

4.8 Analysis of components

The focus within this section lies on integrated components and their characteristics and interfaces for good operation and coordination. Following the theory of nested systems, correlations between a solar cooling system with this integrated system are analyzed while other lower-level dimensions are grayed out (see Figure 4-24).

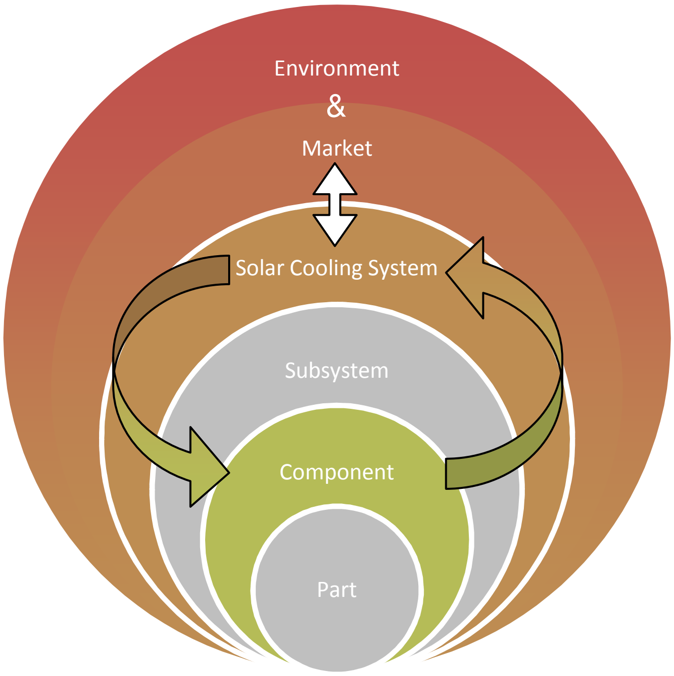


Figure 4-24: Model of Nested systems – Components & Solar Cooling system with Top-Down requirements

Not least because of the huge variety of components, but also for being consistent with the upper-level requirements for good system design, an adequate structure for analyzing components has to be chosen. Applying the developed heat flow model for solar cooling systems (see Figure 4-5 in section 4.4), delivers three appropriate segments for all integrated components. In Table 4-11 the components of the 2007 pilot plant are divided into HEAT, DISTRIBUTION and COOLING.

Table 4-11: Segments for integrated components of a solar cooling system applied to the 2007 pilot plant

Segments for integrated components		
I. HEAT	**II. DISTRIBUTION**	**III. COOLING**
Components for Heat Generation	Components for linking and distributing Heat flow	Components for Cold Generation
• Solar thermal plant • Oil-fired boiler	• Heating circuit • Hot storage tank • Cold storage tank • Cooling circuit	• Sorption chiller • Wet cooling tower

For analyzing the 2007 pilot plant, firstly each component of the 2007 pilot plant was simplified to a model with interfaces to corresponding components of the system. Secondly, the compliance with requirements for good operation of thermal components is considered (see Table 4-12).

Table 4-12: Requirements for good operation of thermal components

Requirements for good operation of thermal components	
1. Durability and Reliability	Low wear, protection against overheating or freezing, supply guarantee
2. Efficiency	High efficiency during operation, low standby losses, low pressure drops, high capacity factor for direct usable heat, low consumption of fossil resources
3. Synergies for improved operation	Known synergies from additional components, synergies for coordination, synergies for other components
4. Hydraulics and Coordination	Coordination of involved components, hydraulic connections and control interfaces for good coordination

Within the following sections, the requirements for good operation are applied to evaluate components and to identify aspects to be improved for optimized system design.

4.8.1 Analysis of solar thermal components for heat generation

Analyzing the solar thermal system of the 2007 pilot plant delivers four components for heat generation and one hydraulic connection to distribution components (see Figure 4-25).

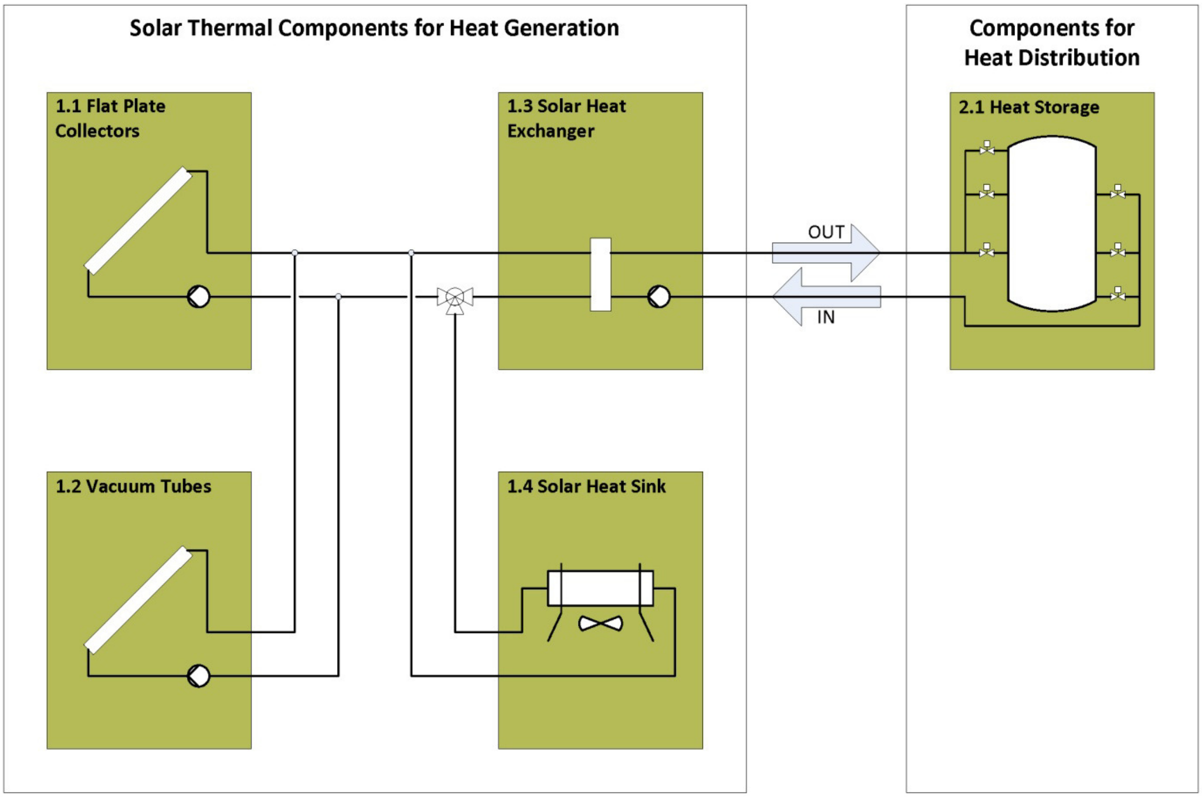


Figure 4-25: Solar thermal components for heat generation with interface to distribution components

Two solar thermal fields in parallel consisting of flat plate collectors (see 1.1 in Figure 4-25) and vacuum tubes (see 1.2 in Figure 4-25) are absorbing solar irradiation for heat generation. Within the primary circuit, filled with anti-freeze-fluid, a heat rejection system (see 1.4 in Figure 4-25) is installed outside for transferring solar thermal surplus to the environment. In case of full storage capacity, this heat sink prevents overheating and keeps the system operable for further heat generation if needed. The solar thermal gains are linked to the heat storage via a plate heat exchanger (see 1.3 in Figure 4-25). With temperature difference control, charging the storage tank (see 2.1 in Figure 4-25) starts with a temperature higher than that at the bottom of the tank. Depending on the delivered solar supply temperature, the installed valves at the storage are controlled to change the charging level from the bottom to the middle and at least to the top of the tank. Within the following, the design and operating characteristics of the solar thermal components are analyzed regarding the benchmarks for good operation of thermal components (see Table 4-13).

Table 4-13: Evaluation of solar thermal components for heat generation

Requirements (for good operation of thermal components)		**Solar Thermal Components** Operation modes of the 2007 pilot plant: **A. Solar-assisted Heating** **B. Solar-assisted Cooling**
1. Durability and Reliability	**a) Operation with low wear**	☑ **YES** Low corrosion by antifreeze fluid within the primary circuit, Low wear through moderate temperatures while operating
	b) Protection against overheating/ freezing	☑ **YES** Protection against overheating through heat sink, Protection against freezing through anti-freeze fluid
	c) Supply guarantee	☒ **NO** General Supply guarantee through solar heat sink, which keeps the solar collectors temperature operable, but far too slow supply with heat at a sufficient temperature
2. Efficiency	**a) High thermal efficiency during operation**	☑ **YES** High solar thermal gains through temperature difference control. Because of low average fluid temperature during operation leading to low thermal losses
	b) Low standby-losses	☑ **YES** No Standby losses
	c) Low pressure drops	☒ **NO** A high number of hydraulic elements, especially for charging the heat storage, lead to a high pressure drop
	d) High capacity factor for direct usable heat	☒ **NO** Low ratio of direct usable solar thermal generated heat, because of insufficient temperature, resulting from temperature difference control
	e) Low consumption of fossil resources	☒ **NO** High consumption of electricity because of a large amount of electric drives, inefficient pumps and a high pressure drop
3. Synergies for improved operation	**a) Additional components for synergies**	☑ **YES** The heat storage tank allows to gain thermal energy from fluctuating global irradiation

	b)	**Synergies for coordination**	☒ **NO** Unknown
	c)	**Synergies for other components**	☒ **NO** Unknown
4. Hydraulics and Coordination	a)	**Good coordination of involved components**	☒ **NO** No coordination between the flat plate collectors and the vacuum collectors, leading to an undetermined temperature within the primary circuit
	b)	**Good hydraulic connections**	☒ **NO** Poor connections between the two collector types. Far too complex charging system of the heat storage
	c)	**Good control interfaces**	☒ **POOR** Only communicating with the heat storage for temperature difference control

The analysis of solar thermal components confirmed the former results of analyzing subsystems, as a pure focus on optimized stand-alone operation does not necessarily lead to optimized system operation. Furthermore, only focusing on a high efficient solar thermal heat generation by temperature difference control, leads to several negative effects for involved components. The insufficient generated temperature delivers a poor supply guarantee, a low capacity factor for direct usable heat and does not cause any synergies for the overall system. Another weakness is the high number of actuators leading to inefficient hydraulics and a high consumption of electricity. Achieved synergies by the heat storage are not transferred to other components as a result of the missing overall perspective. This fact, combined with weak hydraulics and coordination, leads to a poor benchmarking result for the solar thermal components of the 2007 pilot plant.

4.8.2 Analysis of oil-fired boiler components for heat generation

For the analysis of heat generation via the oil-fired boiler, three distribution components and one cooling component could be identified to be involved (see Figure 4-26). The heating circuit with convectors (see 2.2 in Figure 4-26), the sorption chiller (see 3.1 in Figure 4-26) and the heating circuit with fan-coils (see 2.3 in Figure 4-26) are supplied by the oil-fired boiler (see 1.5 in Figure 4-26). The solar thermal gains are used by linking the return-flows of the heat consumers through the heat storage tank (see 2.1 in Figure 4-26) for a return-flow boost of the oil-fired boiler.

The model of corresponding components delivers two hydraulic interfaces between corresponding segments - one between the segment heat generation and the segment distribution and another between distribution and cooling. By considering the discharging strategy of the heat storage tank by a return-flow boost of the fossil driven boiler, it is clear why this system is not suitable for giving priority to renewable heat generation. In every case that solar thermal gains are used to cover heating demand, the heat flow is linked via the fossil boiler for heating-up to achieve a sufficient temperature.

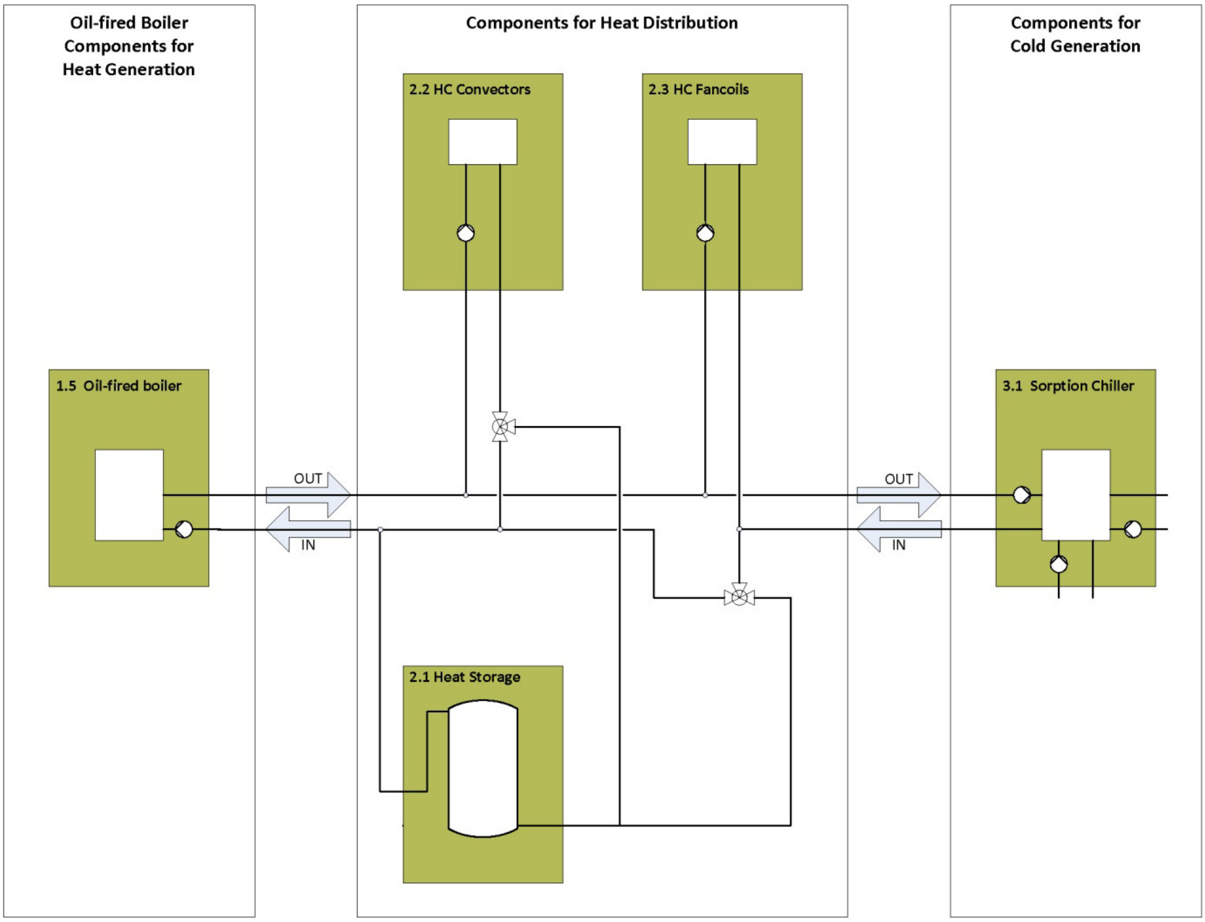


Figure 4-26: Oil-fired boiler components for heat generation with interfaces to distribution and cooling components

Distributing solar thermal generated heat means covering a huge piping distance for linking heat flow to demand. This effort leads to inefficiency by additional thermal losses and pressure drops. Furthermore, this hydraulic weakness also negatively affects the fluid flow for supplying the sorption chiller. The low volume flow resulting from a high pressure drop leads to a limited heat supply performance for the sorption chiller. This happens because of exceeding the optimum temperature difference. Moreover, the achievable temperature difference for providing heat for the sorption chiller leads to security shut-downs of the oil-fired boiler if heat storage temperature is high. Applying the benchmarks for evaluating components, the operation of the oil-fired boiler is analyzed in detail (see Table 4-14).

Table 4-14: Evaluation of oil-fired boiler components for heat generation

Requirements (for good operation of thermal components)		**Oil-fired Boiler Components** Operation modes of the 2007 pilot plant: **B. Solar-assisted Heating** **C. Solar-assisted Cooling**
1. Durability and Reliability	**a) Operation with low wear**	☒ **NO** Many start-stop periods with short operation times leads to high wear and enables corrosion from condensate within combustion chamber
	b) Protection against overheating/ freezing	☑ **YES** Protection against overheating through onboard control
	c) Supply guarantee	☒ **NO** Resulting from a the return-flow boost combined with a high pressure drop, the achievable temperature difference is comparably high, which leads to a security shut-down if heat storage temperature is high
2. Efficiency	**a) High thermal efficiency during operation**	☒ **NO** Many start-stop periods cause a poor efficiency during operation with high combustion losses. In addition, heat losses via piping is high resulting from a high piping lenth
	b) Low standby-losses	☒ **NO** High standby losses through short operation times
	c) Low pressure drops	☒ **NO** A high number of hydraulic elements, especially for the return-flow boost cause a high pressure drop
	d) High capacity factor for direct usable heat	☒ **POOR** Heat characteristics (volume flow and temperatures) only fit to the heating circuit with convectors. Insufficient heat supply for sorption chiller and heating circuit (too high temperature difference, too low volume flow)
	e) Low consumption of fossil resources	☒ **NO** High consumption of fuel oil because if inefficient operation, high consumption of electricity through high pressure drops

3. Synergies for improved operation	**a)**	**Additional components for synergies**	☒ **NO** Unknown
	b)	**Synergies for coordination**	☒ **NO** Unknown
	c)	**Synergies for other components**	☒ **NO** Unknown
4. Hydraulics and Coordination	**a)**	**Good coordination of involved components**	☒ **POOR** Only communicating with the heating circuit consisting of convectors
	b)	**Good hydraulic connections**	☒ **NO** Too complex and inefficient piping, supplying three components with the heat storage tank connected in series. Through too much involved components undetermined operation conditions appear
	c)	**Good control interfaces**	☒ **NO** Only interface for communicating with heating circuit with convectors

The benchmarking of the oil-fired boiler according to good operation illustrates the huge potential for improved system design. This result confirms the high influence of system architecture and coordination for the performance of a component and its impacts on others.

4.8.3 Analysis of components for cold generation

The model from abstracting cooling components and involved components during operation, leads to two cooling components with hydraulic interfaces to the heat generation and distribution segment (see Figure 4-27).

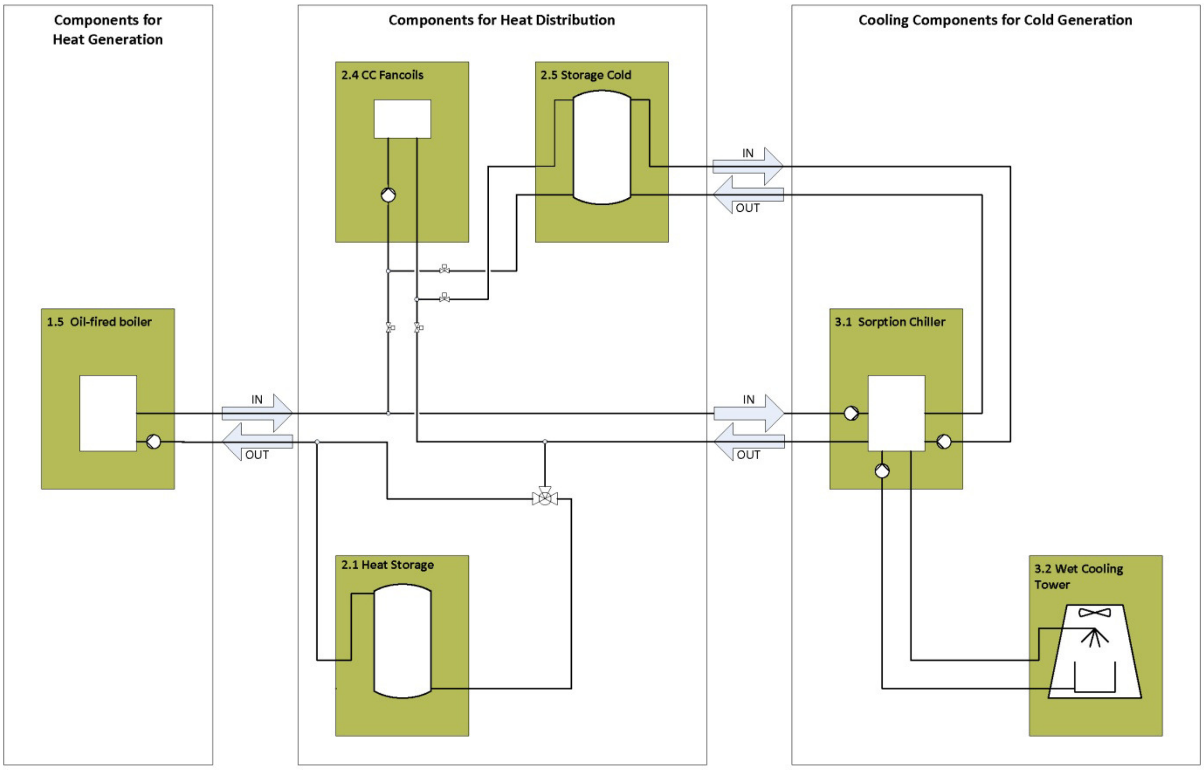


Figure 4-27: Cooling components for cold generation with interfaces to distribution and heat generation components

The sorption chiller (see 3.1 in Figure 4-27) covers the cooling load by linking the building's heat plus the heat flow for driving the sorption process to the wet cooling tower (see 3.2 in Figure 4-27), for transferring to the environment. For heat supply, the sorption chiller is connected to the oil-fired boiler (see 1.5 in Figure 4-27) and via a 3-way-valve with the heat storage tank (see 2.1 in Figure 4-27). For cooling, the sorption chiller supplies a storage tank (see 2.5 in Figure 4-27) with cooled fluid, which is used for heat transfer via fan coils (see 2.4 in Figure 4-27).

Regarding the benchmarks for good operation a detailed analysis of components for cold generation is given in Table 4–15.

Table 4-15: Evaluation of cooling components for cold generation

Requirements (for good operation of thermal components)			Cooling Components Operation modes of the 2007 pilot plant: A. Solar-assisted Cooling
1. Durability and Reliability	a)	Operation with low wear	☒ NO Depending on global irradiation - Many start-stop periods with short operation times leads to high wear. Permanent operation of vacuum pump for ensuring sufficient operation conditions
	b)	Protection against overheating/ freezing	☒ NO Limited protection against freezing through onboard control (chiller and wet cooling tower)
	c)	Supply guarantee	☒ NO No communication for heat demand to provide a sufficient cooling load
2. Efficiency	a)	High thermal efficiency during operation	☒ NO Poor efficiency through insufficient heat supply (a low supply temperature with a high difference between supply and return-flow). In addition, heat losses via piping is high, resulting from a long heat supply
	b)	Low standby-losses	☒ NO High standby losses through long start-up phases, short operation times and long shut-down phases
	c)	Low pressure drops	☒ NO A high number of hydraulic elements, especially for the heat supply cause a high pressure drop
	d)	High capacity factor for direct usable heat	☒ POOR Long start-up and shut-down periods of the chiller and insufficient heat supply (a low supply temperature with a high difference between supply and return-flow) lead to a poor thermal efficiency In addition, heat losses via piping is high
	e)	Low consumption of fossil resources	☒ NO High consumption of fuel oil because of insufficient solar thermal heat supply. High consumption of electricity through high pressure drops, permanent operation of vacuum pump and no speed control for Wet cooling tower (pump and fan)

3. Synergies for improved operation	**a)**	**Additional components for synergies**	☑ **YES** The cold storage tank allows cold generation, even if not demanded,
	b)	**Synergies for coordination**	☒ **NO** Unknown
	c)	**Synergies for other components**	☑ **YES** The cold storage improves the efficiency of the solar thermal plant, as heat surplus can be used for cold generation
4. Hydraulics and Coordination	**a)**	**Good coordination of involved components**	☒ **POOR** Communicating with the cooling circuit, the wet cooling tower, the cold and the heat storage, but without demanding heat supply
	b)	**Good hydraulic connections**	☒ **NO** Too complex and inefficient piping for heat supply with the heat storage tank and the oil-fired boiler connected in series. Too much involved components - undetermined operation conditions appear
	c)	**Good control interfaces**	☒ **POOR** Only interface for communicating with cooling circuit with fan coils

The benchmarking shows the transfer of shortcomings from heat supply to the components for cold generation. Despite a closed information loop between cold production and cooling demand, the open information for heat supply leads to poor operating conditions. Driving the sorption chiller means to be directly influenced by minimum of three other components, resulting from three hydraulic and information interfaces - the high temperature (HT) interface for heat supply, the low temperature (LT) interface for cooling and the middle temperature (MT) interface for heat rejection. If only one connected component does not work correctly, the operation of the sorption chiller, and therefore cold generation, is negatively influenced. Apart from shortcomings resulting from system architecture, weak points of the sorption chiller component itself occurred. For example poor protection against freezing and complex start-up and shut-down phases lead to high error sensitivity of the component.

4.8.4 Analysis of distribution elements

The analysis of components for heat and cold generation delivered a heterogeneous implementation of distribution elements without an indicated system architecture. Regarding the 2007 pilot plant, distribution components are implemented for enabling heat flows between components without harmonizing the different segment tasks. The benchmarking shows the possibility of creating synergies via good combination of components. The implementation of the cold storage tank enables good operating conditions for the LT-side of the sorption chiller, and moreover, improves the operation of the connected cooling circuit. In case of the heat storage tank, operation of the solar thermal components could be improved by integrating and smoothing of intermittent solar irradiation.

The possibility to implement synergies via good combination with distribution components is one key aspect for good system design.

4.9 Analysis of parts

For completing the analysis of a solar cooling system following the theory of nested systems, the role of integrated parts and single pieces is addressed in this section. Parts and single pieces are hydraulic and control elements which are implemented for connecting or coordinating components or which are integrated within components. Therefore, correlations between a solar cooling system with parts implemented for good system architecture are considered as well as correlations between components and integrated parts being analysed (see Figure 4-28).

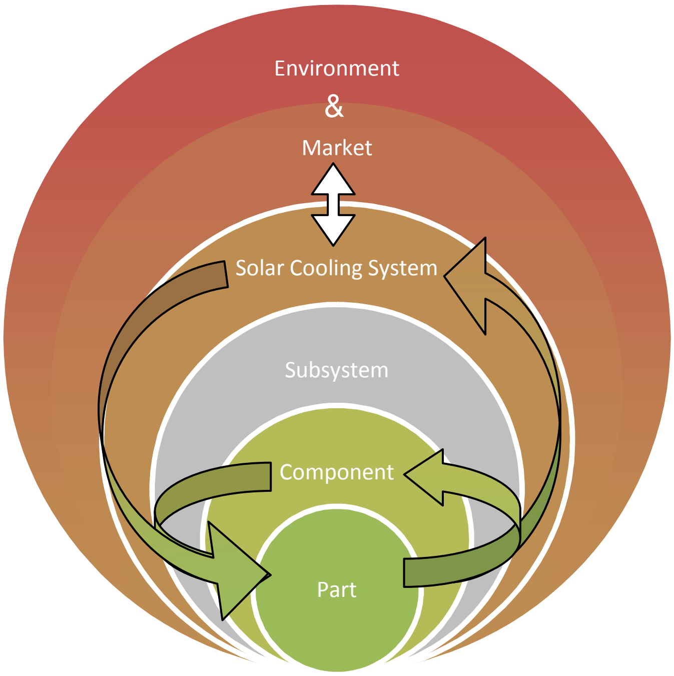


Figure 4-28: Model of Nested systems – integrated parts with components & Solar Cooling system with Top-Down requirements

During previous analysis identified parts being relevant for this work are hydraulic elements such as pumps, valves and heat exchangers. For coordination, some of those have electric drives and control interfaces. Hydraulic and control parts assembled within components can only be changed by choosing another component. However, if assembled within components, hydraulic and control parts should enable a good operation, following the benchmarks for components (see Table 4-12 in section 4.8). For example, high quality parts ensure high durability and reliability of thermal components.

If pumps and valves are implemented as hydraulic elements for coordinating operation of components, the benchmarks for optimized thermal system design (see Table 4-10 in section 4.6) have to be considered, to ensure good system architecture with good coordination. To enable these roles for parts and single pieces within a solar cooling system leads to one general requirement – the priority for high efficient technology with sufficient hydraulic and control interfaces.

4.10 Model of requirements for designing solar cooling systems

Following the theory of nested systems, evaluated requirements of upper –level and lower-level systems are transferred to the investigational level of designing solar cooling systems (see Figure 4-29).

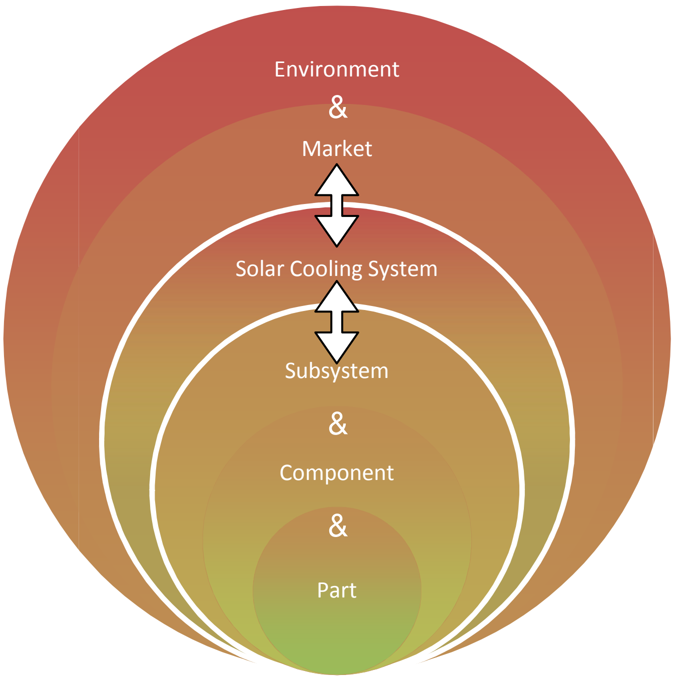


Figure 4-29: Model of Nested systems – transfer of upper and lower level requirements to the investigational level

For completing the requirements for an optimized design of solar cooling systems, the results of analyzing nested systems are combined via synthesis of the model of upper-level requirements (see Figure 4-20 in section 4.5.3) with the requirements for good optimized system design (see Table 4-10 in section 4.7.5) and with requirements for good operation of thermal components (see Table 4-12 in section 4.8). Including the priority for efficient technologies and methods delivers a model of requirements for good system architecture with good coordination and operation (see Figure 4-30). Within the following chapter this model will be applied for generic design of solar cooling systems.

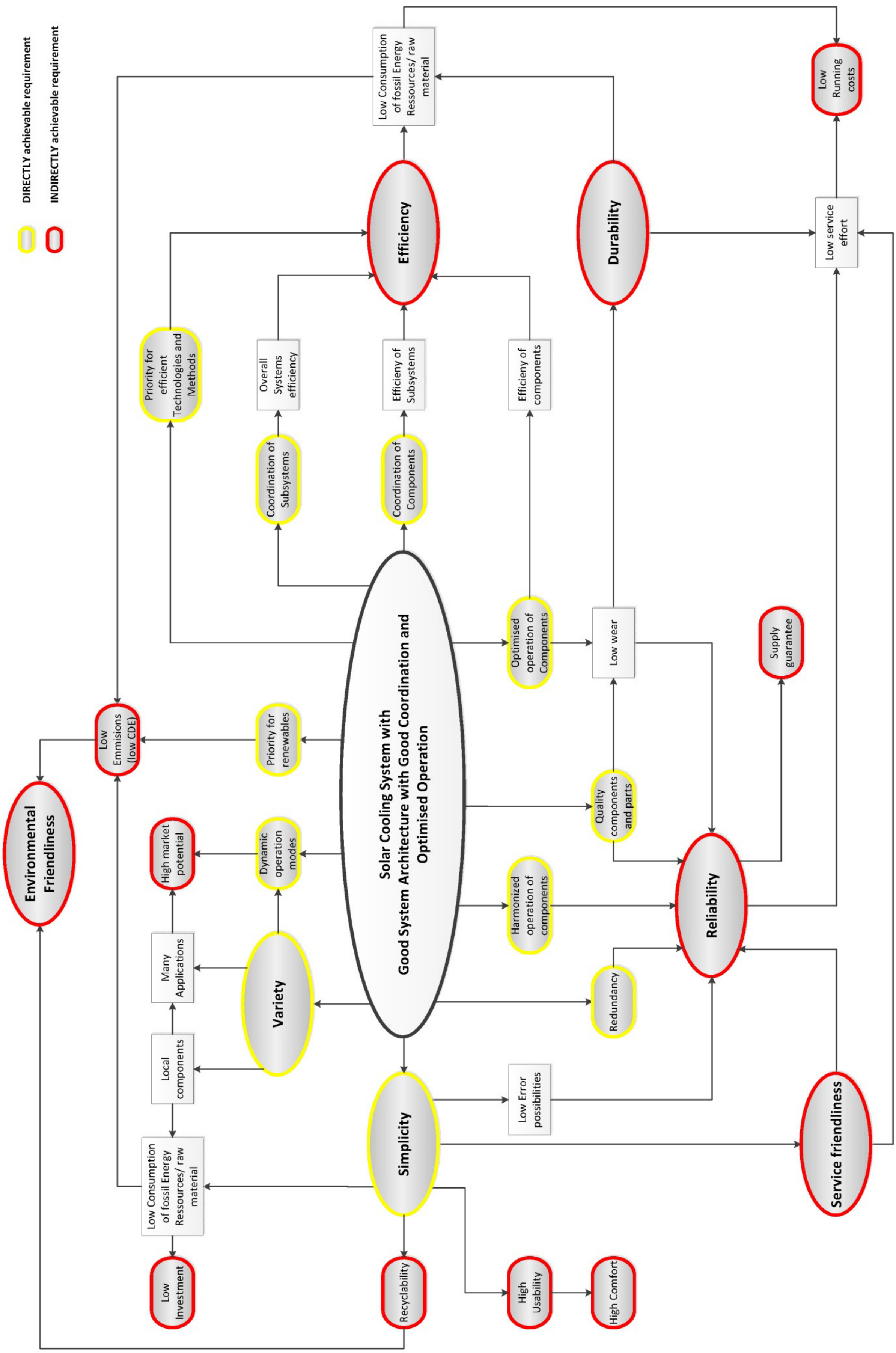


Figure 4-30: Model of requirements for good system architecture with good coordination and operation

4.11 Summary of analysis

This chapter has described the analysis of solar cooling systems based on combining holistic thinking with elementary scientific methods and with established engineering proceedings, thus leading to the theory of nested systems. The appliance of this novel methodology for integrated scientific and engineering work delivered a concise model guiding through analysis. Via abstraction from an environmental level down to an abstraction level consisting of parts, a complete analysis without over sizing the regarded system was ensured. Furthermore, this novel methodology lead to new scientific methods by multidimensional perspectives regarded. The method for developing heat flow models by declaring heat transfer interfaces (HDC-modeling), supplemented with the GLD-method, delivered an efficient and concise proceeding for analyzing system architecture and coordination as well as evaluating operation modes of thermal systems. With requirements resulting from analysis an applicable model for optimized thermal system design was created. These multilayer requirements with correlation between, illustrate target oriented characteristics as a starting point for optimized generic design of solar cooling systems.

5. Theoretical background and generic design

5.1 Preamble

From analysis in chapter 4, a model of requirements (see Figure 4-30) is given as a starting point for designing solar cooling systems. Within this chapter, a methodology is presented to develop a generic design by transferring general requirements for compliant system specifications. The theory of nested systems is used to guide the development of concepts for hydraulics and controls, applying novel methods such as the HDC-heat flow model and the GLD-method. Via the method of entropy generation minimization, the novel concepts and operation principles are proven, leading to optimized specifications for heat generation, distribution and cold generation components. The generic design phase is then processed bottom-up, beginning with generic components for system integration and leading to system configurations for optimized solar cooling systems.

5.2 Design based on a Model of Nested Systems

Following the theory of nested systems, the design of optimized solar cooling systems is guided via a model consisting of four design levels. (see Figure 5-1). Hereby the design of the integrated level for system architecture, the level for operating components and the level of parts, together lead to an optimized generic design for solar cooling systems.

Figure 5-1: Model of Nested systems – Design levels for direct achievable characteristics and requirements

For a guided design process, the model illustrated in Figure 5-1, is supplemented with direct achievable characteristics and requirements resulting from analysis (see Figure 4-30 in section 4.10). To avoid misunderstandings, from the declarations “requirements” and “characteristics”, both meanings are clarified for this work. Here, requirements are meant to be unspecified, e.g. “Simplicity” or “Variety”. Characteristics are more detailed concerning the design, e.g. “Redundancy” or “Dynamic operation modes”. The difference between both declarations involves having an idea of how to implement the original requirement – or not. In the case of “Redundancy”, this characteristic improves the requirement “Reliability”.

For designing each level, surrounding requirements and characteristics first have to be transferred to the appropriate level. Then, existing characteristics are combined with the novel ones, preventing negative effects emerging and enabling synergies if possible.

5.3 Design concept for system architecture

Following the theory of nested systems for designing system architecture, yields three groups of identified characteristics and requirements. Firstly, requirements to be transferred from the surrounding solar cooling system. Secondly, novel characteristics resulting from the model of requirements, and thirdly already established ones applied during analysis via the GLD-method. Within the following, the upper-level requirements simplicity, variety and the priority for renewable and efficient technologies and methods, are transferred to the appropriate design level of system architecture (see Figure 5-2).

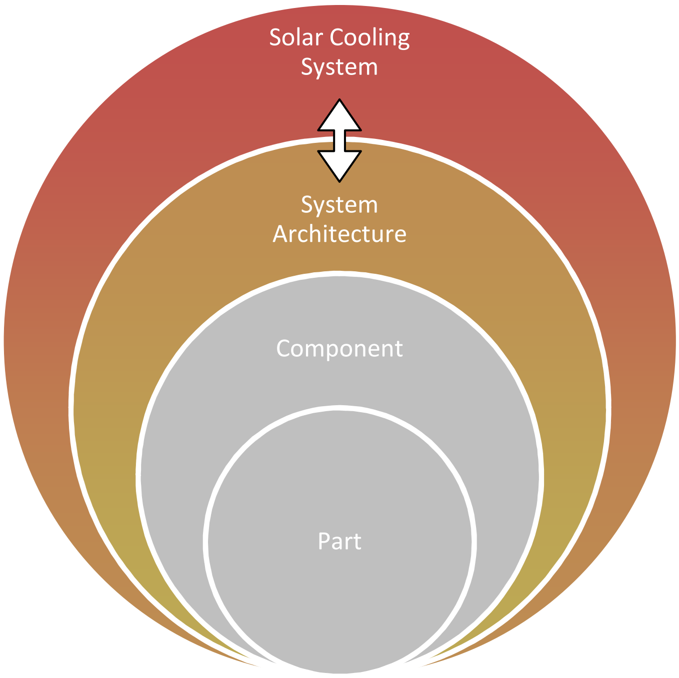


Figure 5-2: Model of Nested systems – transfer of upper level requirements to the design level of system architecture

To enable priority for efficient technologies and methods for system architecture, the proven HDC–heat flow model supplemented with the GLD-Method is identified to be applicable for good design of system architecture.

Transferring priority for renewable energy forms to the investigational level of system architecture means providing a concept for managing heat generation. The generic concept shown in Table 5–1, including demand, fossil and renewable energy generation was developed following a systematic minimization of entropy generation.

Table 5-1: General energy concept with priority for renewable energy sources

General energy concept with priority for renewable energy sources	
Priority for appliance	Description
1. **Optimize Demand**	**Optimize demand** via efficient applications, prevent unnecessary energy conversions, short supply length, control demand
2. **Intermittent renewable energy forms**	Intermittent renewable energy forms (e.g. sun, wind) for **directly covering demand** and **charging energy storage**
3. **Stored Intermittent renewable energy forms**	Stored intermittent renewable energy forms for **indirectly covering demand** via **discharging energy storage**
4. **Dispatchable renewable energy forms**	Dispatchable renewable energy forms (e.g. biomass) for **directly covering demand**
5. **Dispatchable fossil energy forms**	Dispatchable fossil energy forms (e.g. fuel oil, natural gas) for **directly covering peak load demand**

Implementing the generic energy concept for system architecture leads to a central role of the thermal storage for enabling priority for renewable energy forms.

For preventing negative emerging effects, the contradictive requirements “Variety” and “Simplicity” are transferred to the characteristic “Modularity”, combining advantages of both origins. Variety for system architecture means to enable operation of a high variety of heat and cold generation components as well as providing various types of distribution circuits for heating and cooling. For simplicity, a modular system architecture leads to a minimum number of elements involved for each application. Furthermore, a modular thermal energy system strengthens reliability and service friendliness.

With requirements and characteristics, hydraulic and control specifications for system architecture are developed (see Table 5-2). Via the GLD-method, the model of requirements and the generic energy concept, general requirements are transferred to system characteristics leading to hydraulic and control specifications for system architecture.

Table 5-2 Transfer of requirements via characteristics to design specifications for System Architecture

Requirements → for optimized thermal systems including: - **GLD-method** - **General energy concept** - **Model of requirements**	**Characteristics** → a) Heating Mode **b)** Cooling Mode	**Specifications for System Architecture** A. Hydraulic specification B. Control specification
1. Closed chain for heat flow	☑ **YES** **A. Heating Mode** Closed overall loop: **(G-L-D)** heat generation, charging of heat storage, discharging heat storage to heating circuits ☑ **YES** **B. Cooling mode** Closed overall loop: **(G-L-D-G-L-D)** heat generation, charging of heat storage, discharging heat storage to cover demand of sorption chiller, linking of generated cold fluid to the cold storage, discharging cold storage to cover cooling load via cooling circuits	**A. Hydraulics** Closed hydraulic connections for enabling heat flow between components **B. Control** N/A
2. Minimization of involved elements	☑ **YES** **A. Heating Mode** Shortest linking of heat flow: **(G-L-D)** heat generation, charging of heat storage, discharging heat storage to heating circuits ☑ **YES** **B. Cooling mode** Shortest linking of heat flow: **(G-L-D-G-L-D)** heat generation, charging of heat storage, discharging heat storage to cover demand of sorption chiller, linking of generated cold fluid to the cold storage, discharging cold storage to cover cooling load via cooling circuits	**A. Hydraulics** Hydraulic connections for shortest linking of heat flow from HEAT Component via DISTRIBUTION components to COOLING components. Low number of hydraulic elements **B. Control** Low number of control elements
3. Closed loop for information	**A. Heating mode** ☑ **YES** Closed overall loop: **(G-L-D)** heat generation, charging of heat storage, discharging heat storage to heating circuits	**A. Hydraulics** N/A **B. Control** Sufficient interfaces for each involved component and actuator for communication between demand and generation, while enabling a minimum number of control elements

	B. Cooling mode ☑ **YES** Closed overall loop: **(G-L-D-G-L-D)** heat generation, charging of heat storage, discharging heat storage to cover demand of sorption chiller, linking of generated cold fluid to the cold storage, discharging cold storage to cover cooling load via cooling circuits	
4. Demand-oriented generation	**A. Heating mode** ☑ **YES** Temperature and performance of supplied renewable and fossil generated heat is caused by heating demand. **B. Cooling mode** ☑ **YES** Temperature and performance of supplied renewable and fossil generated heat is caused by heat demand of sorption chiller, caused by cooling demand from cooling circuits	**A. Hydraulics** N/A **B. Control** Coordination of involved components and actuators with sufficient interfaces for each, enabling communication between demand and generation, while ensuring a minimum number of control elements
5. Modularity (Simplicity and Variety)	☑ **YES** **A. Heating Mode** Modular thermal energy system enabling a high variety off heat generation components, and various types of distribution circuits for heating ☑ **YES** **B. Cooling mode** Modular thermal energy system enabling a high variety off heat and cold generation components, and various types of distribution circuits for heating and cooling	**A. Hydraulics** Provide hydraulic separation for heat generation and distribution components via connecting to storage tank for modular system architecture and independent operation. Enabling hydraulic interfaces for a variety of generation and distribution components **B. Control** Provide compatible interfaces for a variety of components, while focusing a minimum number of control elements. Provide target-temperature control for combining various heat sources and sinks
6. Priority for Renewables	☑ **YES** **A. Heating Mode** Priority for renewable generated and stored heat for covering heating demand ☑ **YES** **B. Cooling mode** Priority for renewable generated and stored heat for providing heat demand of sorption chiller for renewable cold generation	**A. Hydraulics** Enable Hydraulic separation for each heat generation unit for independent operation. Provide specific charging volumes with priority for renewables **B. Control** Enable coordination of heat generation and distribution components with priority for renewables via target temperature control

7. Priority for efficient Technologies and Methods	☑ **YES** - General Energy concept - GLD-Method - Good engineering design for implementation	**A. Hydraulics** Good design of piping, and actuator dimensions for low pressure drops and low heat leaks **B. Control** Interfaces for speed control and for turning off devices to save electricity, Enable target temperature control for high capacity factor of direct usable heat
8. Redundancy (Reliability)	☑ **YES** Redundancy of heat and cold generation components	**A. Hydraulics** Modular thermal energy system with hydraulic separation for each redundant component enabling independent operation **B. Control** Enable control of redundant components
9. Dynamic operation modes	☑ **YES** Enable combined heating and cooling modes	**A. Hydraulics** Enable hydraulics for distribution to cover heating and cooling demand **B. Control** Provide heating and cooling modes for distribution circuits
10. Coordination of components	☑ **YES** Coordination of heat and cold generation components	**A. Hydraulics** N/A **B. Control** Enable coordination of heat generation and distribution components via sufficient control Interfaces for sensors and actors
11. Harmonized operation	☑ **YES** Enable harmonized operation between each component involved	**A. Hydraulics** Enable hydraulic separation for independent operation of components **B. Control** Include best operation characteristics for stand-alone operation and harmonize with system architecture through providing target-temperature control for combining various heat sources and sinks

Processing the transfer of requirements and characteristics often yielded similar specifications, which confirms the potential for synergies when implementing the identified specifications. For more clarity the deduced hydraulic and control specifications are summarized in Table 5–3.

Table 5-3: Hydraulic and control specifications for designing system architecture

Hydraulic and Control Specifications for Good System Architecture with good Coordination
A. Hydraulic specifications - Implement hydraulic connections for shortest linking of heat flow from HEAT Component via DISTRIBUTION components to COOLING components. - Provide a minimum number of hydraulic elements - Provide hydraulic separation for heat generation and distribution components via connecting to storage tank for modular system architecture and independent operation - Enable hydraulic interfaces for a variety of generation and distribution components - Provide specific charging volumes with priority for renewables - Ensure good design of piping, and actuator dimensions for low pressure drops and low heat leaks - Enable modular thermal energy system with hydraulic separation for each redundant component leading to independent operation - Enable hydraulics for distribution to cover heating and cooling demand
B. Control specifications - Provide a minimum number of control elements - Enable sufficient interfaces for each involved component and actuator for communication between demand and generation - Provide coordination of involved components and actuators - Enable communication between demand and generation - Provide compatible interfaces for a variety of components - Provide target-temperature control for combining various heat sources and sinks - Enable coordination of heat generation and distribution components with priority for renewables via target temperature control - Provide interfaces for speed control and for turning off devices to save electricity - Enable target temperature control for high capacity factor of direct usable heat - Enable control of redundant components - Provide heating and cooling modes for distribution circuits - Enable coordination of heat generation and distribution components via sufficient control Interfaces for sensors and actors - Include best operation characteristics for stand-alone operation and harmonize with system architecture through providing target-temperature control for combining various heat sources and sinks

The hydraulic and control specifications shown in Table 5-3 enable the generic design of system architecture for optimized solar cooling systems.

Applying the theory of nested systems for design provides a guided process for system design. As attributes of integrated parts are a result of conditions given by surrounding systems, the architectural concept for solar cooling systems is designed first, leading to compliant design of integrated components and parts. Consisting of hydraulics and controls, system architecture will be created via a hydraulic design concept leading to the conceptual design of controls.

5.3.1 Design concept for hydraulic architecture

Following the theory of nested systems for design, a concept for hydraulic architecture is created regarding the demanded specifications (see Table 5–3). The generic concept is designed applying the HDC-heat flow model and the GLD method for optimized system architecture with good coordination (see Figure 5-3).

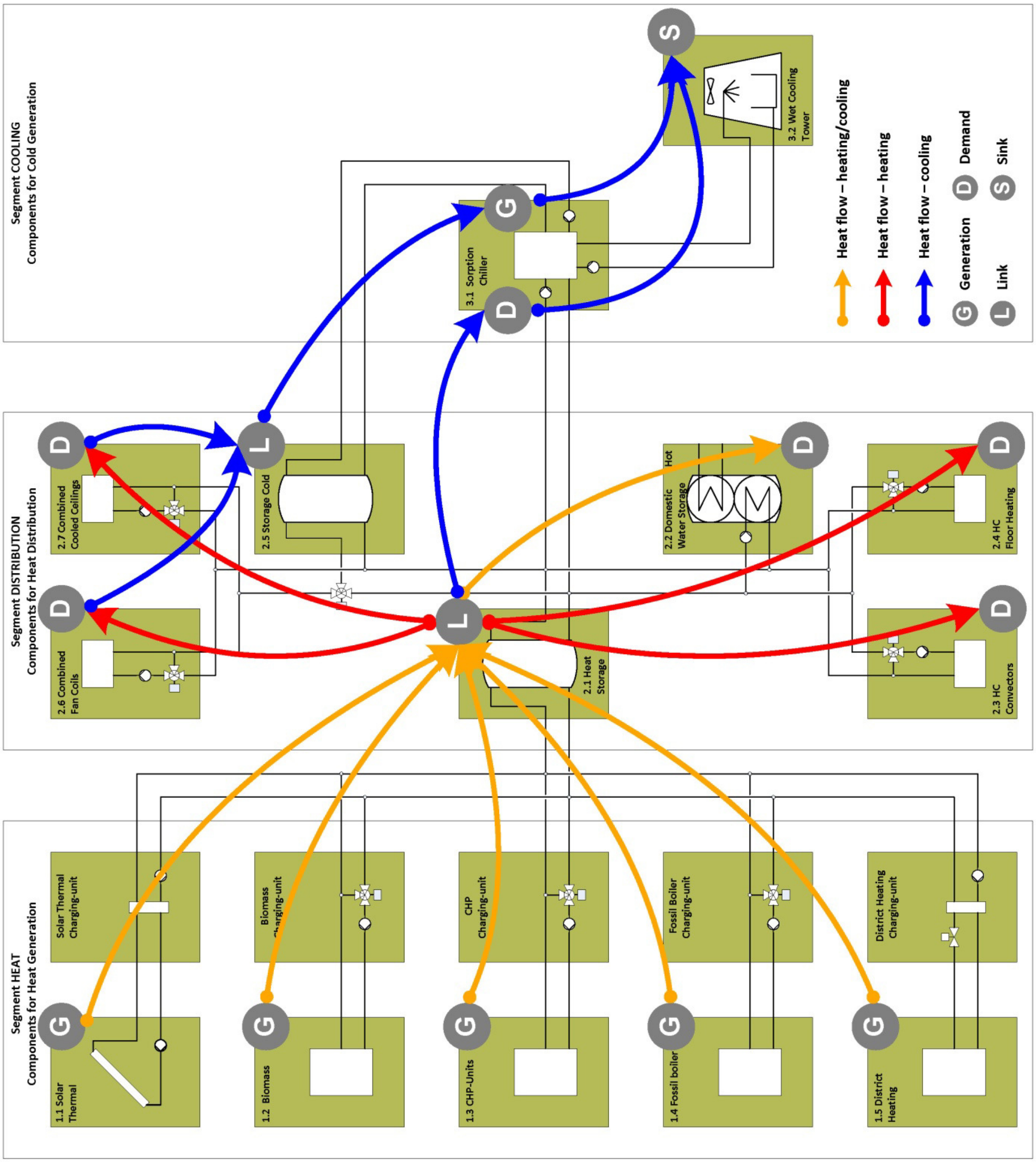


Figure 5-3: Generic design concept for hydraulic architecture via GLD-Method

This modular thermal energy concept provides various types of heat generation units, while always achieving the shortest linking of heat flows (G-L-D). Following the generic energy concept for priority of renewable intermittent and dispatchable sources, solar thermal and biomass components for heat generation are included. For high efficient renewable and fossil heat generation, the hydraulic architecture is prepared for the operation of CHP-units. To cover peak loads of heat demand and to complete the variety for heat generation components, fossil boilers and components for heat supply via district heating systems are provided.

For all actuators, such as pumps and mixers, interfaces for speed control and for turning off the devices are provided to ensure optimised control and electricity savings via demand-oriented operation.

The design concept illustrates the “central” role of the heat storage tank, as being the “link” for every heat generation component to all demanding heat sinks of the system. For achieving full compliance with the developed specifications for good hydraulic system architecture, the heat storage tank has to be designed in detail concerning the hydraulic separation of components and the need for giving priority to renewable energy sources. Both topics are related to the charging and discharging process, and will be regarded during the embodiment of design within section 5.4.

Furthermore, as an abductive guess the hydraulic separation is estimated to enable synergies for operation.

With a good portion related to the implementation of solar cooling systems, the need for good dimensioning of piping and hydraulic elements cannot completely be covered via system architecture. But for encouraging good engineering design depending on specific applications, customized subsystem can be created for the market. Pre-configured modules lead to a moderate engineering effort for specific application of generic design of solar cooling systems (see chillii® Cooling Kits & chillii® System Design in chapter 9).

5.3.2 Design concept for control architecture

In compliance with hydraulic architecture, the design concept for controls is developed following the GLD-principle for good system architecture. To ensure a modular control system, each component involved in solar cooling is connected to a coordinating system control level (see Figure 5-4). This architecture enables independent control of each component for redundancy on the one hand, and various applications resulting from differing system configurations on the other.

Via the GLD-method, communication between demanding and generating components is ensured for good coordination, while providing a minimum of control elements. Via a graphical user interface (GUI), a high usability will be achieved through having only one human interface for controlling the entire system.

Following the theory of nested systems for design, unsolved tasks from the design level considered can be transferred to the next integrated level.

For enabling sufficient communication, the illustrated interfaces for sensors and actors have to be specified within the following sections. Hereby the compatibility with a variety of components has to be focused to enable synergies helping to prevent over-sizing of the control system. As being based on hydraulic architecture, the task for enabling priority for renewable sources firstly needs to be solved before designing applicable control. It was predicted that target-temperature control (Riechert, Obert 1991) would be essential for efficient and harmonized operation as well as for the priority for renewable sources enabled via good coordinated components. The application of this control strategy for optimized thermal systems will be proved during the embodiment of design for integrated components.

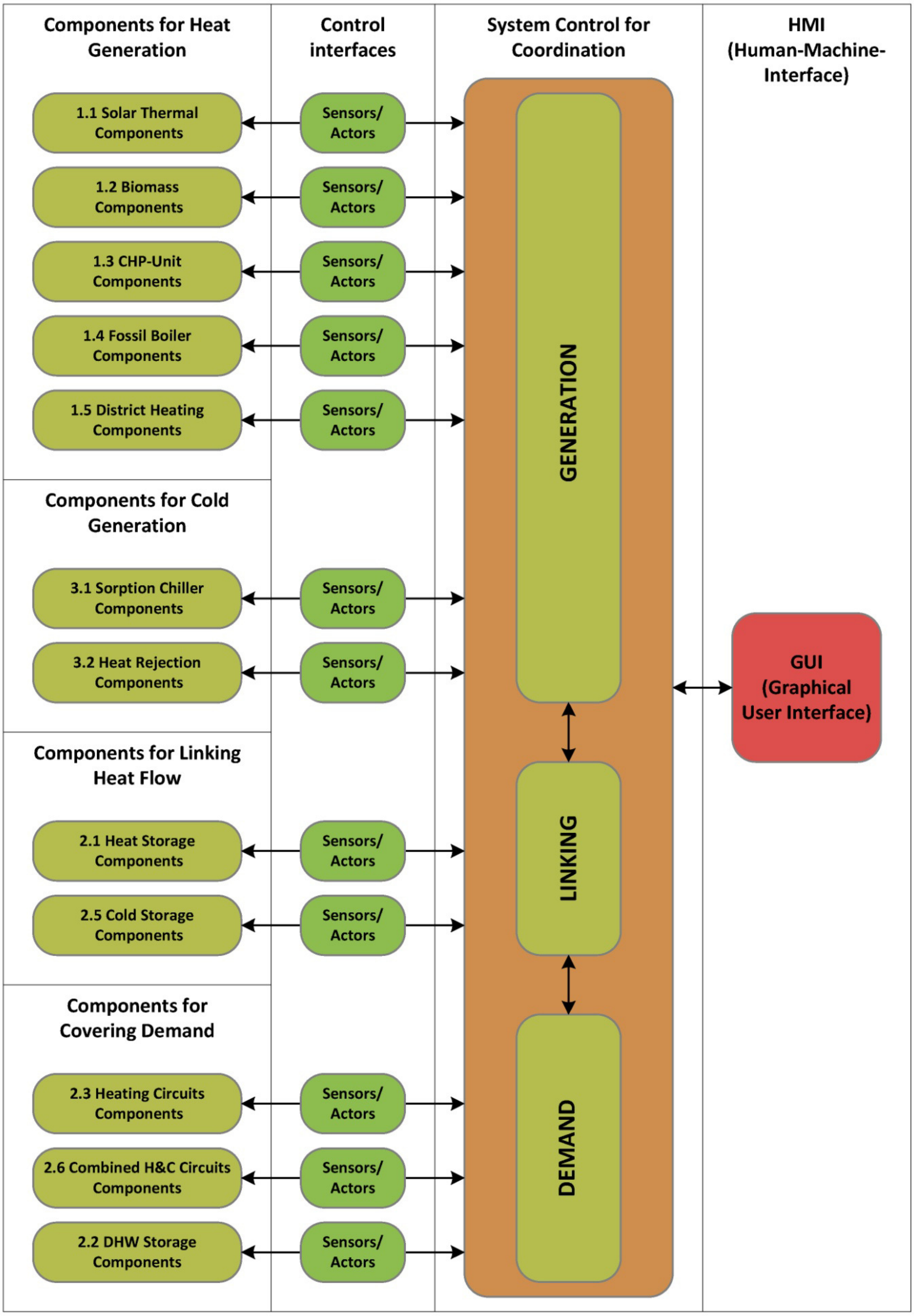


Figure 5-4: Generic design concept for control architecture via GLD-Method

Having prepared the framework for generic design via hydraulic and control architecture, the embodiment of design phase is started within the following section.

5.4 Embodiment of design via integrated components

The embodiment of design is applied via integrating components into the given architecture for solar cooling systems. This surrounding design level delivered specifications and abductive design principles. The theory of nested systems leads to the implementation of upper-level principles through combination with already identified characteristics and requirements being relevant for integrated components (see Figure 5-5).

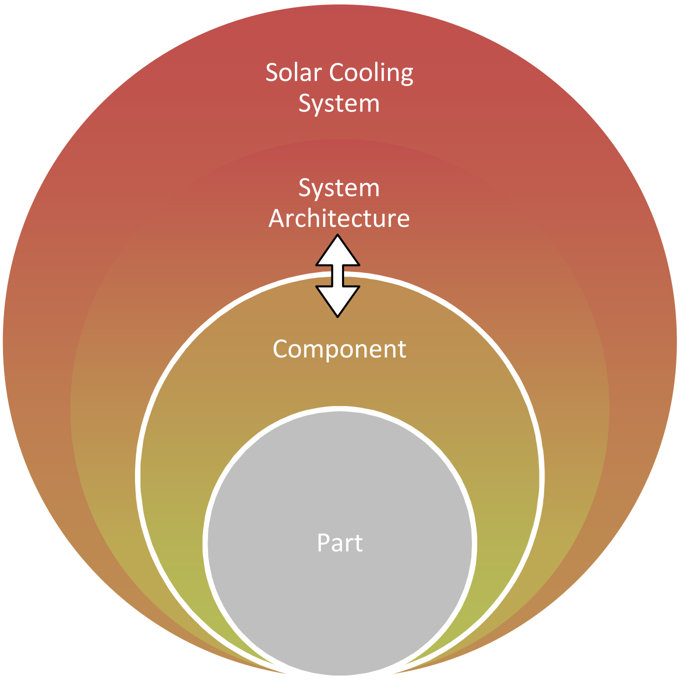


Figure 5-5: Model of Nested systems – transfer of upper level specifications to the design level of components

Regarding specifications from the system architecture level concerning the abductively generated principles, delivers overlapping aspects. Target temperature control (Riechert, Obert 1991) and hydraulic separation both enable synergies. Moreover, combining both principles via cause and effect correlations lead to emergent synergies, for even more improved system design (see Figure 5-6).

Target temperature control delivers demand-oriented supply temperatures for all heat consuming components of a system such as the sorption chiller and the heating circuits. When, for example, the sorption chiller demands heat at a temperature of 80°C, target temperature control leads to generated heat via the solar thermal system at a target temperature of 85°C within the solar collectors. In comparison with the wide spread temperature difference control, target temperature control applied for solar thermal systems leads to lower solar gains caused by the higher average collector temperature while achieving a higher ratio of direct usable heat via considering the required temperature. Temperature difference control, based on the temperature difference between the collector and the storage system, does not consider the temperature demanded by the heat consumers, delivering a sufficient temperature not before the whole storage volume was heated up.

Applying target temperature control to charge the thermal storage enables various heat sources to be combined by generating the same demanded target temperature.

With specifying sufficient control interfaces and best operation conditions for each component, an optimized design of the storage charging and discharging process can be achieved via hydraulic separation and target temperature control. Thus, leading to harmonized operation, and combined with good coordination and independency for each component, enables an efficient and reliable operation. Furthermore, via enabling good coordination, priority for renewable energy sources can be achieved.

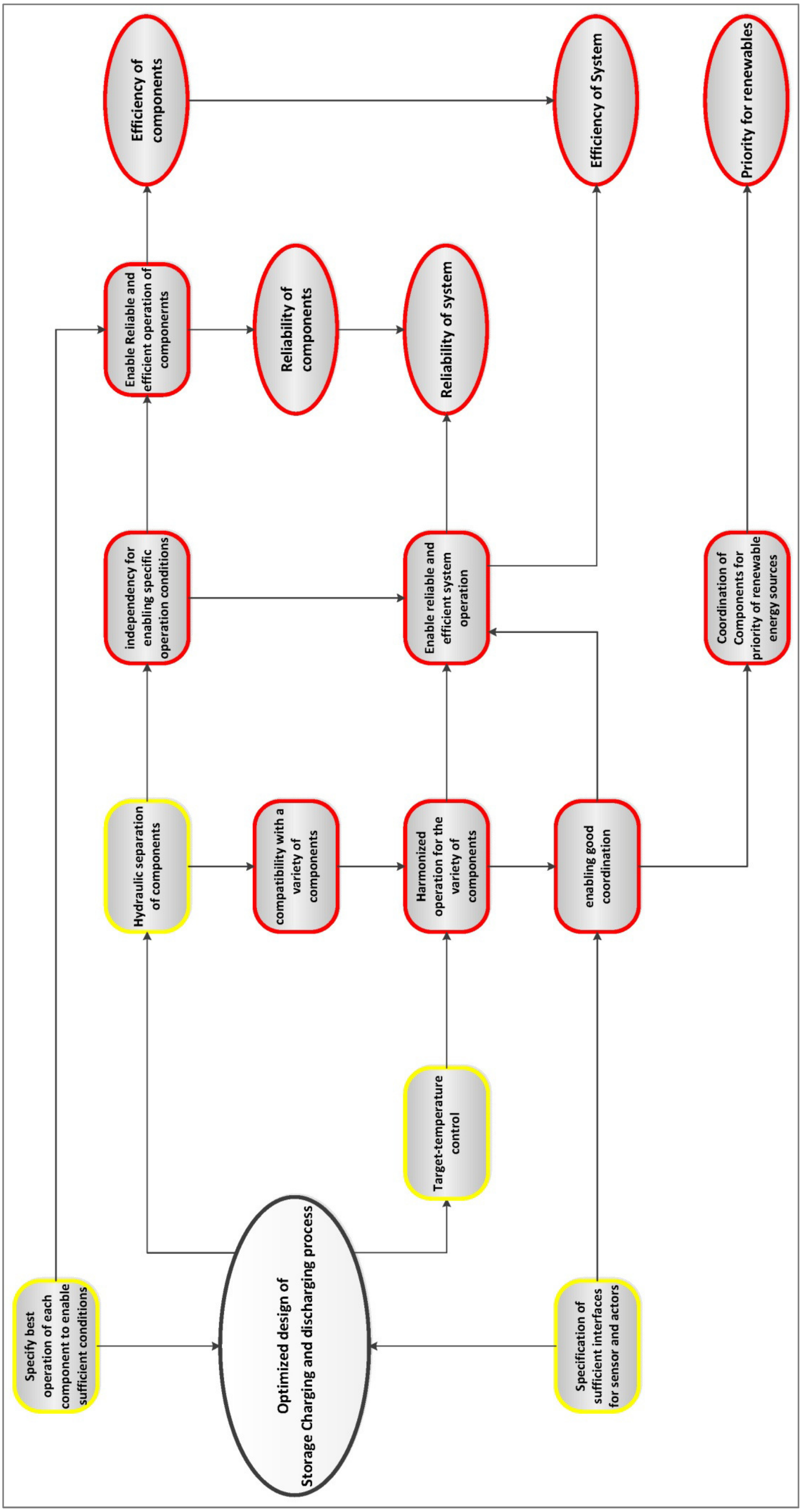


Figure 5-6: Abductively generated principles for improved system design

5.4.1 Thermal storage for optimized system design

Figure 5-7 illustrates the central role of energy storage for demand-oriented heat supply. In compliance with the general energy concept (see Table 5–1), the priority for renewable energy sources covering demand must be coordinated with respect to the given sequence. Hereby, intermittent sources have the highest priority for direct and indirect coverage of demand. Then dispatchable renewable sources such as biomass, are used for heat generation, followed by fossil sources for peak load.

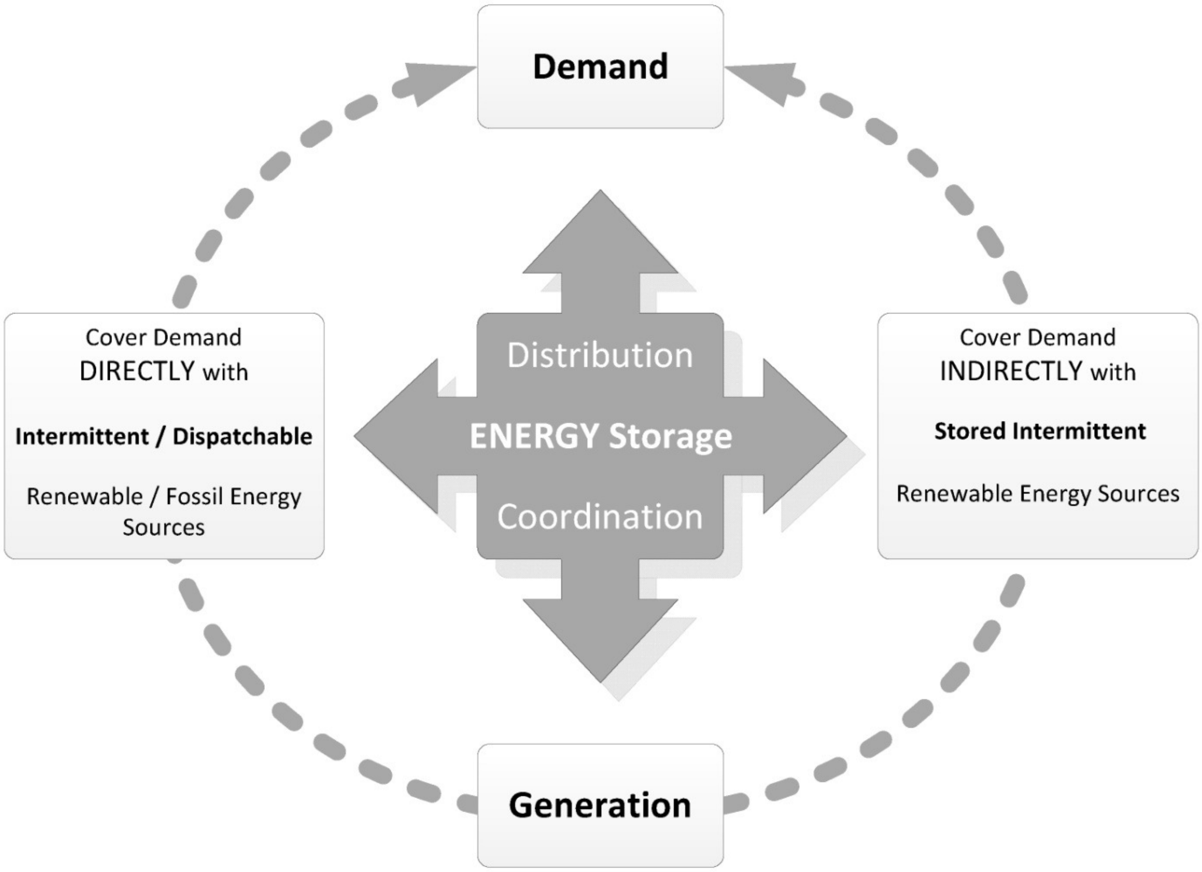


Figure 5-7: The central role of energy storage for demand-oriented heat supply

The energy storage is designed for enabling this sequence, through combining differing heat generation methods via hydraulic separation. This enables the coordination of heat generation via target temperature control, as all components deliver heat with the same demand-oriented temperature. For the efficient linking of heat flows, optimized operation modes for thermal energy storage have to be designed. To evaluate emerging effects for improved efficiency of thermal systems, the method of entropy generation minimization (EGM-method) has been identified during analysis to be essential for this work. Within the following section, this method will be transferred to the design level of components for achieving optimized thermodynamic processes.

5.5 The method of Entropy Generation Minimization (EGM)

The entropy generation minimization method was firstly presented from Adrian Bejan (Bejan 1996). Compared to other thermodynamic methods such as exergy analysis, the EGM-method is focused on minimizing entropy generation for evaluating the quality of the regarded process. Entropy generation leads to irreversible heat, which has no benefit for the process. For thermal system design, the reduction of irreversible heat leads to an improved efficiency of heat and mass transfer processes. Therefore, the EGM-method is identified as essential for good thermal system design.

To analyze thermodynamic systems, three statements towards the regarded process have to be made. These are the conservation of mass, energy and entropy. Equation (5-1)shows the balancing of mass.

$$\sum_{\mathrm{in}} \dot{\mathrm{m}} - \sum_{\mathrm{out}} \dot{\mathrm{m}} = \frac{\partial \mathrm{M}}{\partial \mathrm{t}} \qquad (5\text{-}1)$$

The first law of thermodynamics for open systems [see Equation (5-2)] gives the energy balance.

$$\sum_{in} \dot{m} \left(h + \frac{1}{2}V^2 + gZ\right) - \sum_{out} \dot{m} \left(h + \frac{1}{2}V^2 + gZ\right) + \dot{Q} - \dot{W} = \frac{\partial E}{\partial t} \qquad (5\text{-}2)$$

And the second law of thermodynamics for open systems [see Equation(5-2)], delivers the entropy balance.

$$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \frac{\dot{Q}}{T} \leq \frac{\partial S}{\partial t} \qquad (5\text{-}3)$$

Inequality (5-3) for entropy conservation, shows that entropy can cross the system borders with mass or heat. Moreover, entropy might be generated. A pure reversible process does not generate entropy. But during every real process a specific amount of entropy is generated leading to irreversibility. Inequality (5-4) shows the second law of thermodynamics for open systems with focuses on entropy generation.

$$\dot{S}_{gen} = \frac{\partial S}{\partial t} - \frac{\dot{Q}}{T} + \sum_{out} \dot{m}s - \sum_{in} \dot{m}s \geq 0 \qquad (5\text{-}4)$$

The EGM-method is applied by evaluating system configurations to find characteristics with minimum entropy generation, in order to achieve maximum efficiency.

5.5.1 Thermodynamic model of thermal storage

The appliance of the EGM-method for thermal system design requires an adequate model for proceeding. Recall that previous investigations increased the storage efficiency via enabling a good stratification within the tanks. However, the presented work assumed complete charging and discharging of the storage, leading to focus on perfectly stratified systems represented by a thin thermocline within the tank which separates the zones of different temperatures. It is obvious, that mixing, thermal diffusion or convection negatively affects the extraction rate during every complete charging and discharging cycle. But when operating a real system, charging and discharging is processed simultaneously and might not be completed more than once a day. Losses resulting from “preparing” the stratification cannot be avoided, but the frequency of establishing a thermocline can be reduced by decreasing the number of complete charging and discharging cycles. When harmonizing the amount of charging and discharging energy, the established stratification can be preserved during the operation period, leading to lower losses considering the entire operating period (see Figure 5-8).

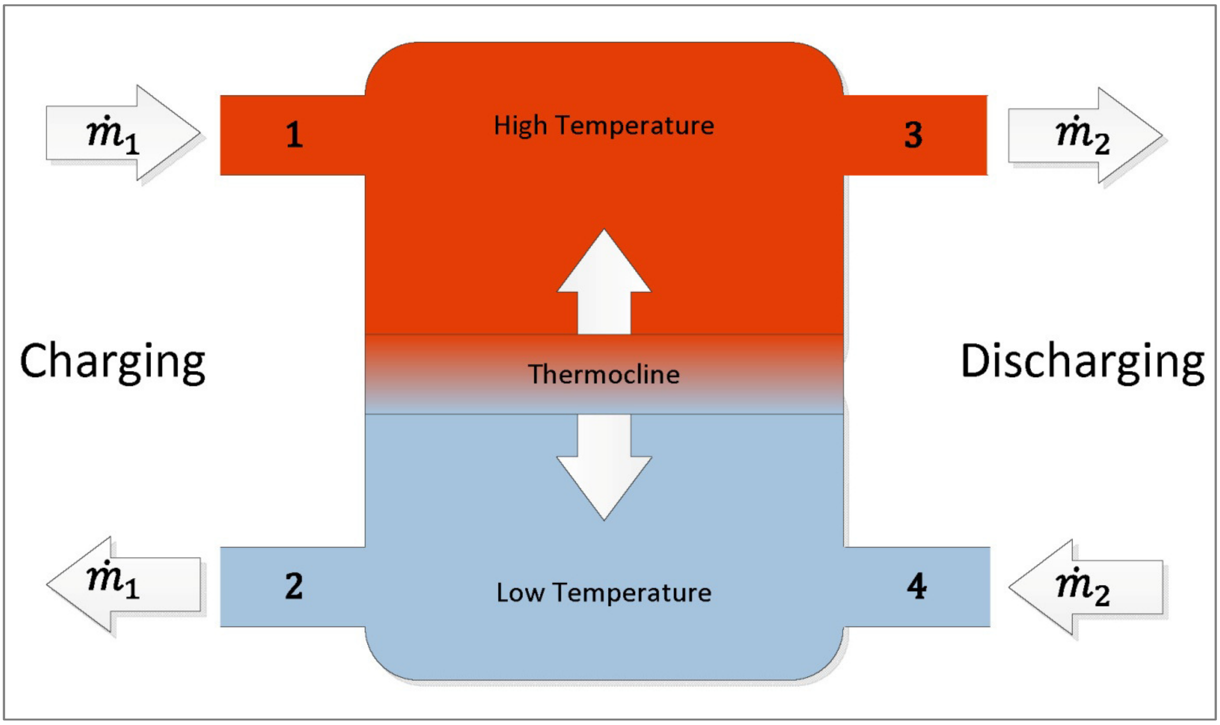


Figure 5-8: Principle of charging and discharging process

This principle of reducing the frequency of establishing a thermocline by focusing on preserving the existing stratification is investigated via the EGM-method.

To evaluate the efficiency of a thermal storage operated with target temperature control and harmonized charging and discharging, an open thermodynamic model with ports for mass transfer was created. Figure 5-9 illustrates an abstracted thermal storage tank with two inlet and three outlet ports.

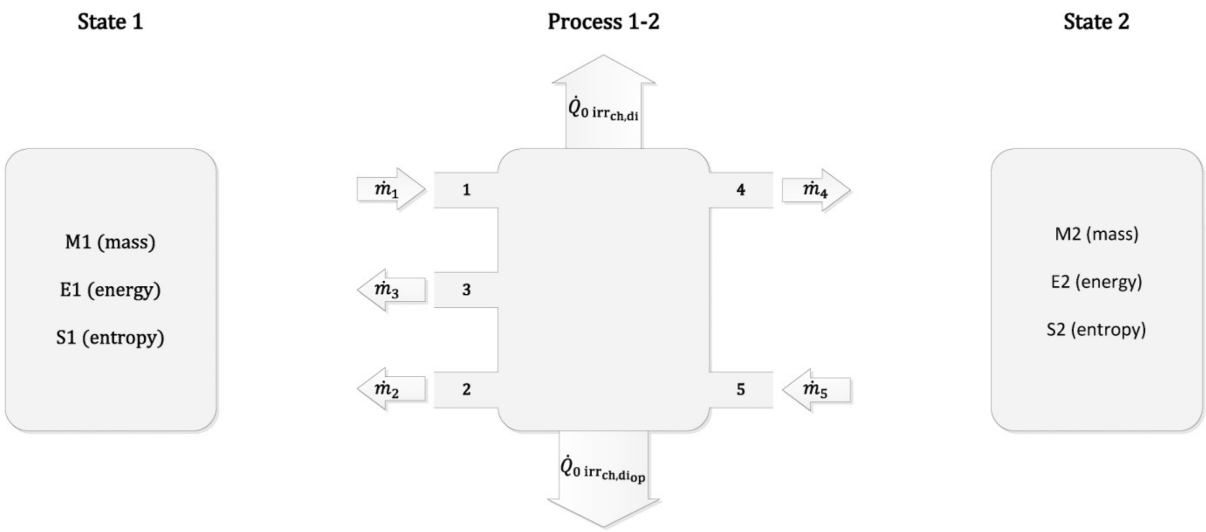


Figure 5-9: Open thermodynamic system based on a model of thermal storage

Between state 1 and state 2, the process 1-2 takes place. Process 1-2 includes two operation phases – first charging and last discharging labeled with subscript $[]_{ch,di}$, and charging and discharging during operation labeled with subscript $[]_{ch,di\ op}$. The first charging of the storage is processed via ports 1 and 2. The last discharging of the thermal storage takes place via ports 4 and 5. During operation, ports 1 and 3 are used for charging and ports 4 and 5 are used for discharging. This configuration represents a real case, consisting of a heat generation unit with supply flow to the storage and return flow back from the storage tank. As well as a heat consumer with a supply flow to the heat sink and a return flow back to the storage tank. The reason for the two different return flow ports back to the heat generation unit (see ports 2 and 3 in Figure 5-9) is caused by differing temperatures of the storage mass during the phases. At the beginning of the process, the storage temperature is equal to the environment T_0. Therefore, the first charging is needed to prepare operation conditions. If working with an adiabatic model, the last discharging represents the ratio of energy which can be used from the first charging process. During operation, there are multiple charging and discharging cycles.

The flow through the system is defined as steady. That means that net inflow is equal to net outflow, and all system properties, such as density, specific energy and specific entropy do not change regarding state 1 and state 2. The mass conservation statement for the regarded system is given by Equation (5-5).

$$\sum_{in} \dot{m} - \sum_{out} \dot{m} = 0 = \dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4 + \dot{m}_5 \tag{5-5}$$

As working with an ideal, incompressible fluid with a low flow velocity within the storage tank, work on volume is not included. As Re << Re_{krit}, representing laminar flow, pressure drops from fluid friction during the process have a very low influence for this model, and are therefore not considered. Pressure is defined to be constant during process1-2. Considering these conditions, Equation (5-6) delivers the energy balance of the process.

$$\sum_{in} \dot{m}h - \sum_{out} \dot{m}h - \sum_{out} \dot{Q} = 0$$
$$= \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 - \dot{m}_4 h_4 + \dot{m}_5 h_5 - \dot{Q}_{0\ irr_{ch,di}} - \dot{Q}_{0\ irr_{ch,di_{op}}} \quad (5\text{-}6)$$

Recall that the process 1-2 includes two phases, represented within this energy conservation statement by two differing irreversibilities. The entropy balance is illustrated via Equation (5-7).

$$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s - \sum_{out} \frac{\dot{Q}}{T} + \dot{S}_{gen} = 0$$
$$= \sum_{in} \dot{m}s - \sum_{out} \dot{m}s - \frac{\dot{Q}_{0\ irr_{ch,di}} + \dot{Q}_{0\ irr_{ch,di_{op}}}}{T_0} + \dot{S}_{gen} \quad (5\text{-}7)$$

The second law rearranged yields the entropy generation rate of the process shown in Equation (5-8).

$$\dot{S}_{gen} = \frac{\dot{Q}_{0\ irr_{ch,di}} + \dot{Q}_{0\ irr_{ch,di_{op}}}}{T_0} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \quad (5\text{-}8)$$

Considering the relevant mass flows makes clear, that the total rate of entropy generation during the process is equal to the sum of entropy generation rates during the two phases [see Equation (5-9), thus represented by the corresponding mass flows. Hereby the products with $\dot{m}_{ch}$ and $\dot{m}_{di}$represent the “first charging and last discharging” phase, and the products with $\dot{m}_{ch_{op}}$ and $\dot{m}_{di_{op}}$ are relevant during operation.

$$\dot{S}_{gen} = \dot{S}_{gen_{ch,di}} + \dot{S}_{gen_{ch,di_{op}}} \quad (5\text{-}9)$$

Applying Equation (5-9) yields Equation (5-10) for the rate of entropy generation during “first charging and last discharging” phase and Equation (5-11) for entropy generated during operation.

$$\dot{S}_{gen_{ch,di}} = \dot{m}_{ch} \left(\frac{h_1 - h_2}{T_0} + s_2 - s_1 \right) + \dot{m}_{di} \left(\frac{h_5 - h_4}{T_0} + s_5 - s_4 \right) \quad (5\text{-}10)$$

$$\dot{S}_{gen_{ch,di_{op}}} = \dot{m}_{ch_{op}}\left(\frac{h_1 - h_3}{T_0} + s_3 - s_1\right) + \dot{m}_{di_{op}}\left(\frac{h_5 - h_4}{T_0} + s_5 - s_4\right) \qquad (5\text{-}11)$$

Those two entropy statements will be applied for entropy generation minimization within the following sections.

5.5.2 EGM for "first charging and last discharging" phase

The rate of entropy generation during the "first charging and last discharging" phase is given by the general Equation (5-12).

$$\dot{S}_{gen_{ch,di}} = \dot{m}_{ch}\left(\frac{1}{T_0}\sum_{IN-OUT} h_{ch} + \sum_{LT-HT} s_{ch}\right) + \dot{m}_{di}\left(\frac{1}{T_0}\sum_{IN-OUT} h_{di} + \sum_{LT-HT} s_{di}\right) \qquad (5\text{-}12)$$

With defining equal mass flows for charging and discharging in Equation (5-13), the general process is illustrated in Figure 5-10.

$$\dot{m}_{ch} = \dot{m}_{di} = \dot{m}_{ch,di} \qquad (5\text{-}13)$$

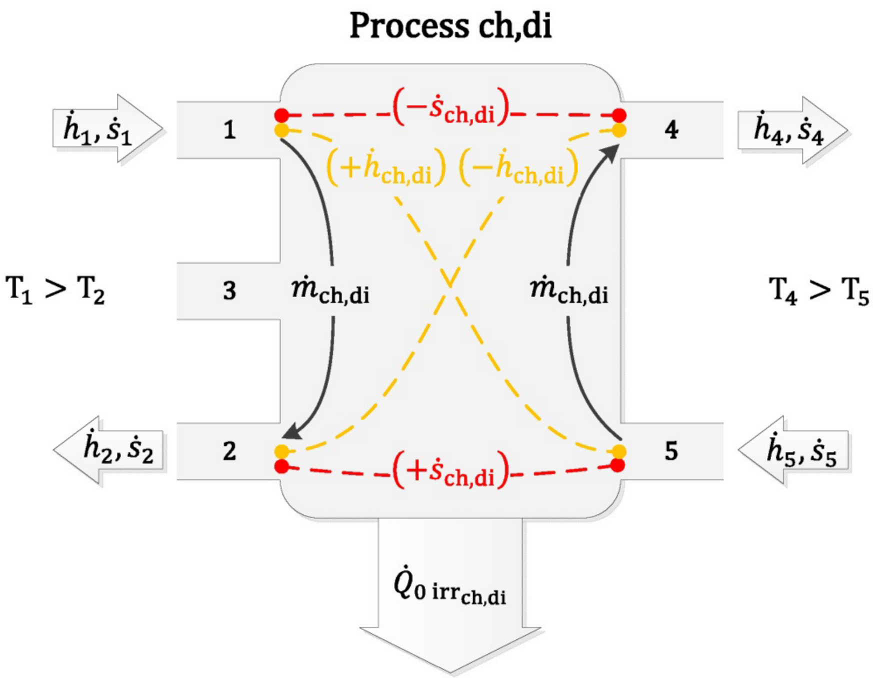


Figure 5-10: General process for first charging and last discharging phase

Combining Equation (5-12) with Equation (5-13) yields Equation (5-14) for calculating the rate of entropy generation with equal mass flows for first charging and last discharging of the storage.

$$\dot{S}_{gen_{ch,di}} = \dot{m}_{ch,di}\left(\frac{1}{T_0}\sum_{IN_{15}-OUT_{24}} h_{ch,di} + \sum_{LT_{25}-HT_{14}} s_{ch,di}\right) \tag{5-14}$$

Equation (5-14) shows that $\dot{S}_{gen_{ch,di}}$ is directly proportional to $\dot{m}_{ch,di}$. With $\dot{m}_{ch,di}$ approaching zero, yields an entropy generation rate also approaches zero [see Equations (5-15)].

$$\begin{aligned} &\dot{S}_{gen_{ch,di}} \propto \dot{m}_{ch,di} \\ &\Rightarrow \dot{m}_{ch,di} \to 0 \\ &\Rightarrow \dot{S}_{gen_{ch,di}} \to 0 \end{aligned} \tag{5-15}$$

Recall, deduced from Equation (5-10), that $\dot{S}_{gen_{ch,di}}$ is directly proportional to $\big(f(T_1 - T_4) + f(T_5 - T_2)\big)$. With $\big((T_1 - T_4) + (T_5 - T_2)\big)$ approaching zero, yields an entropy generation rate which also approaches zero [see Equations (5-16)].

$$\begin{aligned} &\dot{S}_{gen_{ch,di}} \propto \big(f(T_1 - T_4) + f(T_5 - T_2)\big) \\ &\Rightarrow \big((T_1 - T_4) + (T_5 - T_2)\big) \to 0 \\ &\Rightarrow \dot{S}_{gen_{ch,di}} \to 0 \end{aligned} \tag{5-16}$$

For minimized irreversibility during first charging and last discharging of the storage two aspects for EGM are identified. Firstly the supply flow temperatures of connected heat generation and heat consuming units have to be harmonized with target temperature control to minimize ΔT_{1-4}. Secondly the storage mass for preparing operation conditions (heating-up storage mass from $T_0 = T_2$ to T_5) has to be reduced.

5.5.3 EGM for charging and discharging cycles during operation

The entropy statement for charging and discharging during operation is given by Equation (5-17).

$$\dot{S}_{gen_{ch,di_{op}}} = \dot{m}_{ch_{op}}\left(\frac{1}{T_0}\sum_{IN-OUT} h_{ch_{op}} + \sum_{LT-HT} s_{ch_{op}}\right) + \dot{m}_{di_{op}}\left(\frac{1}{T_0}\sum_{IN-OUT} h_{di_{op}} + \sum_{LT-HT} s_{di_{op}}\right) \qquad (5\text{-}17)$$

With defining equal mass flows for charging and discharging in Equation (5-18), the general process is illustrated in Figure 5-11.

$$\dot{m}_{ch_{op}} = \dot{m}_{di_{op}} = \dot{m}_{ch,di_{op}} \qquad (5\text{-}18)$$

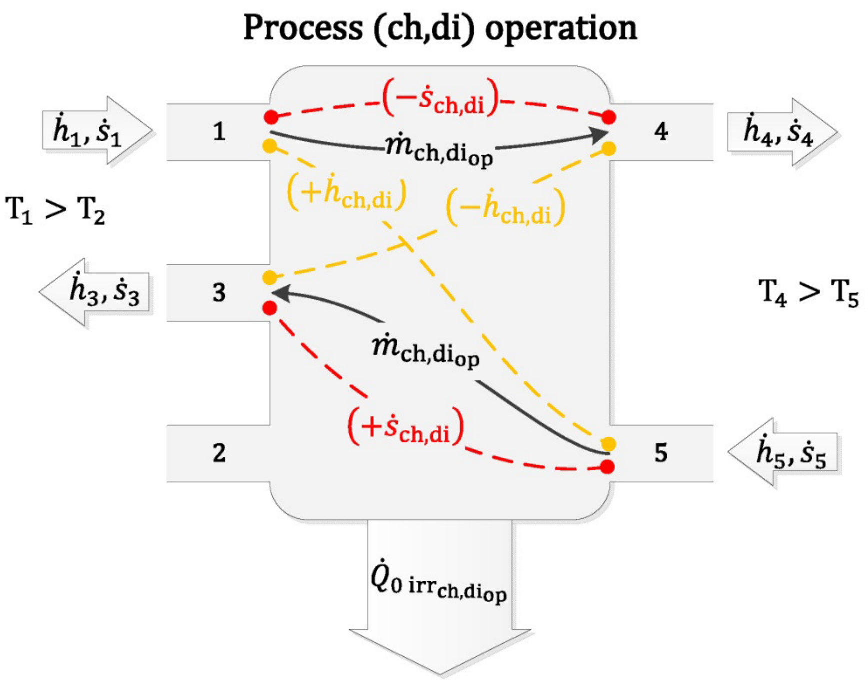


Figure 5-11: General process for charging and discharging during operation

Equation (5-18) inserted into Equation (5-17), yields Equation (5-19) for the rate of entropy generation with equal mass flows for charging and discharging during operation.

$$\dot{S}_{gen_{ch,di_{op}}} = \dot{m}_{ch,di_{op}} \left(\frac{1}{T_0} \sum_{IN-OUT} h_{ch,di_{op}} + \sum_{LT-HT} s_{ch,di_{op}} \right) \tag{5-19}$$

Equation (5-19) shows that the generated entropy during operation is directly proportional to the mass flow through the storage. With the mass flow approaching zero, the entropy generation rate also approaches zero [see Equations (5-20)].

$$\begin{gathered} \dot{S}_{gen_{ch,di_{op}}} \propto \dot{m}_{ch,di_{op}} \\ \Rightarrow \dot{m}_{ch,di_{op}} \rightarrow 0 \\ \Rightarrow \dot{S}_{gen_{ch,di_{op}}} \rightarrow 0 \end{gathered} \tag{5-20}$$

Recall, that Equation (5-11), shows that the rate for entropy generation during operation is directly proportional to $\left(f(T_1 - T_4) + f(T_5 - T_3)\right)$.
$\left((T_1 - T_4) + (T_5 - T_3)\right)$ approaching zero, the entropy generation rate also approaches zero [see Equations (5-21)].

$$\begin{gathered} \dot{S}_{gen_{ch,di_{op}}} \propto \left(f(T_1 - T_4) + f(T_5 - T_3)\right) \\ \Rightarrow \left((T_1 - T_4) + (T_5 - T_3)\right) \rightarrow 0 \\ \Rightarrow \dot{S}_{gen_{ch,di_{op}}} \rightarrow 0 \end{gathered} \tag{5-21}$$

For minimized irreversibility from charging and discharging the storage during operating, several aspects for EGM are identified. In compliance with the investigated phase in section 5.5.2, the supply flow temperatures of connected heat generation and heat consuming units have to be harmonized with target temperature control to minimize ΔT_{1-4}. For achieving a minimum ΔT_{5-3} resulting from return flow temperatures, charging and discharging mass flows should be controlled. For reducing heat losses, firstly supply and return flow temperatures can be reduced, considering temperature requirements of each application. Secondly, the active storage mass should be reduced as well as the ratio of storage surface to mass, which can be achieved via optimized geometry. Thirdly, the overall heat transfer coefficient has to be decreased via good insulation of the storage tank.

5.5.4 EGM-characteristics for optimized thermal storage design

To be applicable for generic design, sources for entropy generation are transferred to abstract characteristics for minimizing entropy generation, leading to specifications for efficient integrated thermal storage design (see Table 5-4).

Table 5-4 Transfer of design characteristics for EGM to design specifications for thermal storage

Causes for Entropy generation $\dot{S}_{gen} = \dot{S}_{gen_{ch,di}} + \dot{S}_{gen_{ch,di_{op}}}$	Design characteristics for EGM $\downarrow \dot{S}_{gen_{ch,di}} + \downarrow \dot{S}_{gen_{ch,di_{op}}} = \downarrow \dot{S}_{gen}$	Specifications for integrated Storage A. Hydraulic specification B. Control specification
Heating-up storage mass (from start-up temperature T_2 to T_5) for achieving operation conditions (demand-oriented temperature) $(\dot{S}_{gen_{ch,di}})$	1. Harmonize supply flow temperatures for a minimum ΔT_{1-4}	A. Hydraulics Ensure same level for inlet and outlet of supply flows from heat generation unit to heat demanding unit. B. Control Provide target temperature control whereby $T_1 \approx T_4$ to achieve $\downarrow \Delta T_{1-4}$
	2. Minimize storage mass $m_{ch,di}$ for pre-heating	A. Hydraulics Provide a minimum storage mass at the top of the storage tank for the pre-heating phase. B. Control Provide target temperature control for top-level charging and discharging whereby $T_1 \approx T_4$ to achieve $\downarrow \Delta T_{1-4}$
	3. Minimize temperature difference ΔT_{5-2} for heating-up storage mass	A. Hydraulics Provide good storage insulation for preserving heat from operation cycles before B. Control Provide steady operation of heat consuming units, to minimize the number of heating-up phases
Charging and discharging cycles of storage during operation $(\dot{S}_{gen_{ch,di_{op}}})$	1. Harmonize supply and return flow temperatures for minimizing ΔT_{1-4} and ΔT_{5-3} via equal mass flows for charging and discharging $\dot{m}_{ch_{op}} \approx \dot{m}_{di_{op}} \approx \dot{m}_{ch,di_{op}}$	A. Hydraulics Ensure same level for inlet and outlet of supply flows from heat generation unit to heat demanding unit. Provide same (lower) level for inlet and outlet of return flows from heat demanding unit to heat generation unit B. Control Provide target temperature control for top-level charging and discharging whereby $T_1 \approx T_4$ to achieve $\downarrow \Delta T_{1-4}$ Provide temperature difference control for heat generation and heat consuming units to achieve $T_5 \approx T_3$ and therefore $\downarrow \Delta T_{5-3}$

Heat losses during pre-heating and operation of the storage $\left(\dot{\boldsymbol{S}}_{\boldsymbol{gen}_{\boldsymbol{ch,di}}} \,\&\, \dot{\boldsymbol{S}}_{\boldsymbol{gen}_{\boldsymbol{ch,di_{op}}}}\right)$	1. Minimize storage mass $m_{ch,di}$ for pre-heating and storage mass $m_{ch,di_{op}}$ for operation	A. Hydraulics Provide a minimum storage mass at the top of the storage tank for pre-heating and operation phase. B. Control Provide target temperature control for top-level charging and discharging whereby $T_1 \approx T_4$ to achieve $\downarrow \Delta T_{1-4}$
	2. Reduce ratio of storage surface to active storage mass $\frac{A_{storage}}{m_{ch,di}}$ for pre-heating and $\frac{A_{storage}}{m_{ch,di_{op}}}$ for operation	A. Hydraulics Find optimum geometry for providing a minimum storage mass at the top of the storage tank for pre-heating and operation phase with a minimum storage surface. B. Control N/A
	3. Reduce supply flow and return flow temperatures to decrease temperature differences ΔT_{14m-0} and ΔT_{53m-0} to the environment	A. Hydraulics N/A B. Control Evaluate minimum target temperature for covering demand
	4. Reduce overall heat transfer coefficient $U_{storage}$ of the storage tank	A. Hydraulics Provide good storage insulation B. Control N/A

Applying the deduced specifications for optimized thermal storage design from Table 5-4 leads to entropy generation minimization. This leads to minimized irreversibility and therefore to maximized efficiency of integrated thermal storage with target temperature control [see Equations (5-22)].

$$\begin{gathered}\downarrow \dot{S}_{gen_{ch,di}} + \downarrow \dot{S}_{gen_{ch,di_{op}}} = \downarrow \dot{S}_{gen} \\ \Rightarrow \downarrow \dot{Q}_{0\ irr_{ch,di}} + \downarrow \dot{Q}_{0\ irr_{ch,di_{op}}} = \downarrow \dot{Q}_{0\ irr} \\ \Rightarrow \frac{\sum_{out} \dot{m}h - \downarrow \dot{Q}_{0\ irr}}{\sum_{in} \dot{m}h} = \uparrow \eta_{Storage}\end{gathered} \qquad (5\text{-}22)$$

5.6 Top-down specification of components and parts

Regarding the theory of nested systems, lower-level systems follow the conditions and rules of the upper-level systems. For designing an optimized overall system, compliant specifications for each regarded level are essential. Therefore, characteristics of components and parts are specified based on given conditions by upper-level and same level systems (see Figure 5-12).

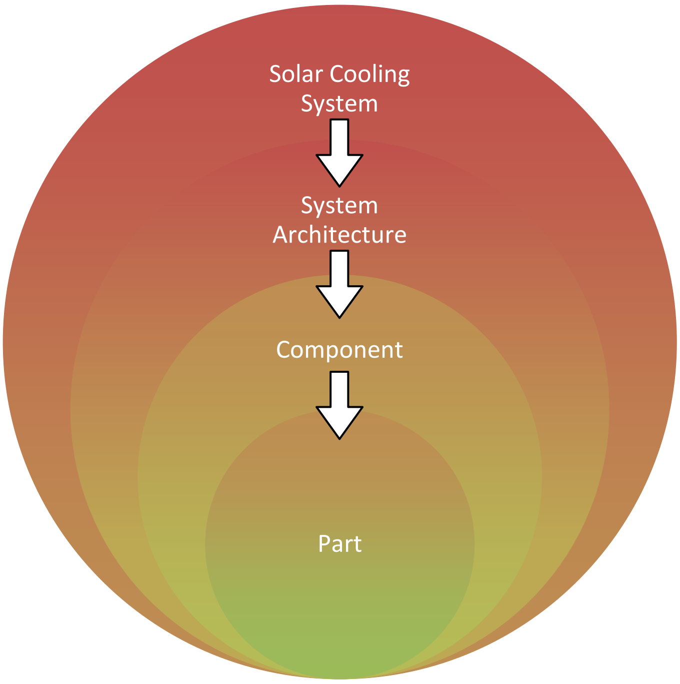


Figure 5-12: Model of Nested systems – Top-down specification

With investigated design characteristics and principles from previous sections, such as the central role of thermal storage and like target-temperature control, specifications for components and parts can be deduced - leading to an integrated design of components, forming an optimized overall system.

5.7 Specifications for integrated design of heat generation and distribution

Recall that a high systems efficiency and priority for renewables can be achieved via an optimized charging and discharging process of the thermal storage (see section 5.4). The design concept for hydraulics and control (see sections 5.3.1 and 5.3.2) deliver the system architecture for thermal systems including the principles of target-temperature-control, hydraulic separation and the priority for renewable sources. By target-temperature-control, the entropy generation during storage processes could be minimized, leading to EGM-characteristics for high efficient thermal storage design (see section 5.5.4). Based on a general energy concept (see section 5.3.1) characteristics for the priority of renewables were formed, leading to a defined operation sequence for involved heat sources.

The achieved findings and characteristics from previous sections are now combined to detail specifications for integrated heat generating and distributing components of a solar cooling system.

5.7.1 Specification of thermal system for priority of renewable sources

Recall that the thermal storage was identified to have a central role for optimized thermal system design. Via this component, hydraulic separation of heat generating and heat consuming units is implemented. Combining EGM-characteristics for high efficient thermal storage design with characteristics for the priority of renewables delivers specifications for an integrated design of thermal storage (see Table 5–5).

Table 5-5 Transfer of characteristics to design specifications for thermal storage

Characteristics for optimized storage design the Priority of Renewables via ensuring a defined sequence for operating heat generation units respecting rules and principles including: - **GLD-method** - **General energy concept** - **Model of requirements** - **EGM-method** - **Priority of Renewables**	**Specifications for an Integrated Thermal storage** Operation with novel system architecture and target-temperature-control A. Hydraulic specification B. Control specification
a) Charging of storage with target-temperature - all heat generation units	**A. Hydraulics** Supply flows of heat generation units are connected to the top of the storage **B. Control** All heat generation units are target-temperature controlled
b) Differing charging volumes for heat generation units, depending on their sequence - all heat generation units	**A. Hydraulics** Return flows connected to lower level for heat generation systems with high priority such as the solar thermal system (big operating volume), and connected to higher level of storage for heat generation systems with low priority such as the fossil heat source (small operating volume) **B. Control** Priority control for all heat generation units
c) Discharging of storage with target-temperature - all heat consuming units	**A. Hydraulics** Supply flows to the heat consuming units are connected to the top of the storage **B. Control** All heat demanding units deliver information for calculating dynamic target temperature of the system
d) **Dynamic storage volumes for charging and discharging depending on “charging-level” of the storage**	**A. Hydraulics** Switching return flows of heat generation and heat consuming units via valves to upper or lower storage level **B. Control** Control valves depending on storage and return flow temperatures

5.7.2 Specification of heat generating components

Within this section the proven characteristics for optimized thermal design are applied to specify heat generating components of the system. Recall, that the principles of target-temperature-control as well as hydraulic separation for each component is ensured via the novel system architecture. Combining with best operating conditions for each component leads to integrated specifications for solar thermal systems, fossil-driven boilers, CHP-units and biomass-driven heat sources. While specifying integrated components, emerging effects from system design are considered. Table 5-6 illustrates developed specifications for solar thermal components.

Table 5-6: Specifications for integrated solar thermal components

Characteristics (for good operation of thermal components)		**Specifications for Integrated Solar Thermal Components** Operation with novel system architecture including - **target-temperature-control** - **hydraulic separation via thermal storage** - **best specific operating conditions**
1. Durability and Reliability	**a) Operation with low wear**	☑ **YES** Low corrosion by antifreeze fluid within the primary circuit, Low wear through moderate temperatures while operating
	b) Protection against overheating/ freezing	☑ **YES** Protection against overheating through heat sink, Protection against freezing through anti-freeze fluid
	c) Supply guarantee	☑ **YES** General Supply guarantee through solar heat sink, which keeps the solar collectors temperature operable, very fast supply with heat at a sufficient temperature which ensures priority for renewable sources
2. Efficiency	**a) High thermal efficiency during operation**	☒ **NO** Lower solar thermal gains compared to temperature difference control, because of a higher average fluid temperature during operation leading to higher thermal losses
	b) Low Standby-losses	☑ **YES** No Standby losses

	c)	**Low Pressure drops**	☑ **YES** a low number of hydraulic elements, combined with a dynamic speed control for pumps (on target-temperature), leads to a lower pressure drop
	d)	**High capacity factor for direct usable heat**	☑ **YES** Expected to deliver highest ratio of direct usable solar thermal generated heat, because of always sufficient temperature, resulting from target-temperature-control
	e)	**Low consumption of fossil resources**	☑ **YES** Low consumption of electricity because of a few electric drives, speed controlled pumps for demand-oriented supply and a low pressure drop
3. Synergies for improved operation	a)	**Additional Components for synergies**	☑ **YES** The heat storage tank allows to gain thermal energy from fluctuating global irradiation
	b)	**Synergies for Coordination**	☑ **YES** Easy coordination because of Target-temperature-control, and therefore obvious charging level of storage system
	c)	**Synergies for other Components**	☑ **YES** Easy coordination of corresponding heat generation units for base and peak load because of Target-temperature-control, and obvious charging level of storage system
4. Hydraulics and Coordination	a)	**Good coordination of involved components**	☑ **YES** Coordination between the flate plate collectors and the vacuum collectors, via target-temperature-control, leading to determined operating conditions and to demand-oriented temperatures
	b)	**Good Hydraulic connections**	☑ **YES** Easy charging system of the heat storage via speed control on target-temperature
	c)	**Good Control interfaces**	☑ **YES** Target-temperature-control for dynamic demand oriented heat generation

Rather than focusing on the highest efficiency of solar thermal components, which traditionally delivers temperature-difference control, the integrated design method leads to focus on the highest systems efficiency with priority for renewable heat sources, which delivers target-temperature-controlled components. In the case of the solar thermal system, this strategy leads to less solar gains while generating more direct usable heat. This effect gets clearer considering the sources for entropy generation while charging the thermal storage investigated in section 5.5. Minimizing temperature differences between heat supply and reducing storage mass, delivers more positive emerging effects such as a higher capacity factor for direct usable energy and a very good supply guarantee compared to the negative effect of reduced collector efficiency. Heat generation units for dispatchable fossil and renewable energy sources such as biomass-driven, oil- and natural gas fired boilers and CHP-units are also operated to charge the central thermal storage. Via target temperature control all market-available types can be combined for various applications. Through the defined sequence for heat generating units the priority of renewables is ensured via differing charging volumes. Moreover, the novel system architecture does enable synergies for the overall thermal system. Table 5-7 illustrates specifications for heat generation units for dispatchable energy sources.

Table 5-7: Specifications for integrated heat generating components for dispatchable energy sources

Characteristics (for good operation of thermal components)		**Specifications for Integrated heat generation units for dispatchable energy sources (biomass, fuel oil, natural gas)** Operation with novel system architecture including - **target-temperature-control** - **hydraulic separation via thermal storage** - **best specific operating conditions**
1. Durability and Reliability	**a) Operation with low wear**	☑ **YES** Few start-stop periods with long operation times leads to low wear and reduces corrosion from condensate within combustion chamber, steady operation with sufficient operation temperature leads to high lifetime of components and integrated parts

	b)	**Protection against overheating/ freezing**	☑ **YES** Protection against overheating through onboard control
	c)	**Supply guarantee**	☑ **YES** Steady and specific operating conditions resulting from hydraulic separation deliver a very high reliability of each heat-generating component. The achieved hydraulic independency enables redundancy of all connected heat sources
2. Efficiency	**a)**	**High thermal efficiency during operation**	☑ **YES** A few start-stop periods with long operation times cause a high efficiency during operation resulting from low combustion and standby losses. In addition, heat losses via piping is very low resulting from short piping lengths
	b)	**Low Standby-losses**	☑ **YES** Low standby losses through long generation times, and complete “off”-times between
	c)	**Low Pressure drops**	☑ **YES** A low number of hydraulic elements, combined with hydraulic separation and speed control for dynamic mass flow cause very low pressure drops
	d)	**High capacity factor for direct usable heat**	☑ **YES** Delivered heat characteristics (volume flow and temperatures) are suitable for all heat consumers resulting from target-temperature and hydraulic separation: sufficient heat supply (temperature and volume flow) for all heat consumers delivers a very high capacity factor for direct usable heat
	e)	**Low consumption of fossil resources**	☑ **YES** Low consumption of fossil energy sources because of priority for renewables, efficient operation of fossil-driven units and a low consumption of electricity through low pressure drops and optimized operation periods
3. Synergies for improved operation	**a)**	**Additional Components for synergies**	☑ **YES** The heat storage tank allows positive emerging effects while combining a high variety of components

	b) Synergies for Coordination	☑ **YES** Easy coordination because of Target-temperature-control and hydraulic separation
	c) Synergies for other Components	☑ **YES** Easy coordination of corresponding heat generation units for base and peak load because of Target-temperature-control, and obvious charging level of storage system
4. Hydraulics and Coordination	**d) Good coordination of involved components**	☑ **YES** System control leading to determined operating conditions and to demand-oriented temperatures
	e) Good Hydraulic connections	☑ **YES** Easy charging systems with a low number of elements involved per component lead to efficient and reliable operation via speed control on target-temperature
	f) Good Control interfaces	☑ **YES** Target-temperature-control for dynamic demand oriented heat generation

5.8 Specifications for integrated design of cold generation and distribution

For integrating within a thermal system, optimum operating conditions for sorption chillers have to be evaluated. Therefore, these units are considered in detail to develop specifications for optimized operation within the thermal system.

5.8.1 Principle of sorption chillers

Market available sorption chillers are divided into absorption and adsorption units, resulting from differing sorbents for operating the sorption cycle. While absorption chillers use a liquid sorbent, adsorption chillers use a solid sorbent. That in fact leads to different machine designs, while using the same principle. The most common working pair for absorption chillers is lithium-bromide and water, while lithium-bromide acts as sorbent and water as refrigerant. Hereby the characteristic of the sorbent lithium-bromide in being a good solvent for the refrigerant water is essential for the sorption cycle. Figure 5-13 shows an abstracted absorption cycle with internal circulation of the refrigerant as well as with heat interfaces to the thermal energy system and to the environment.

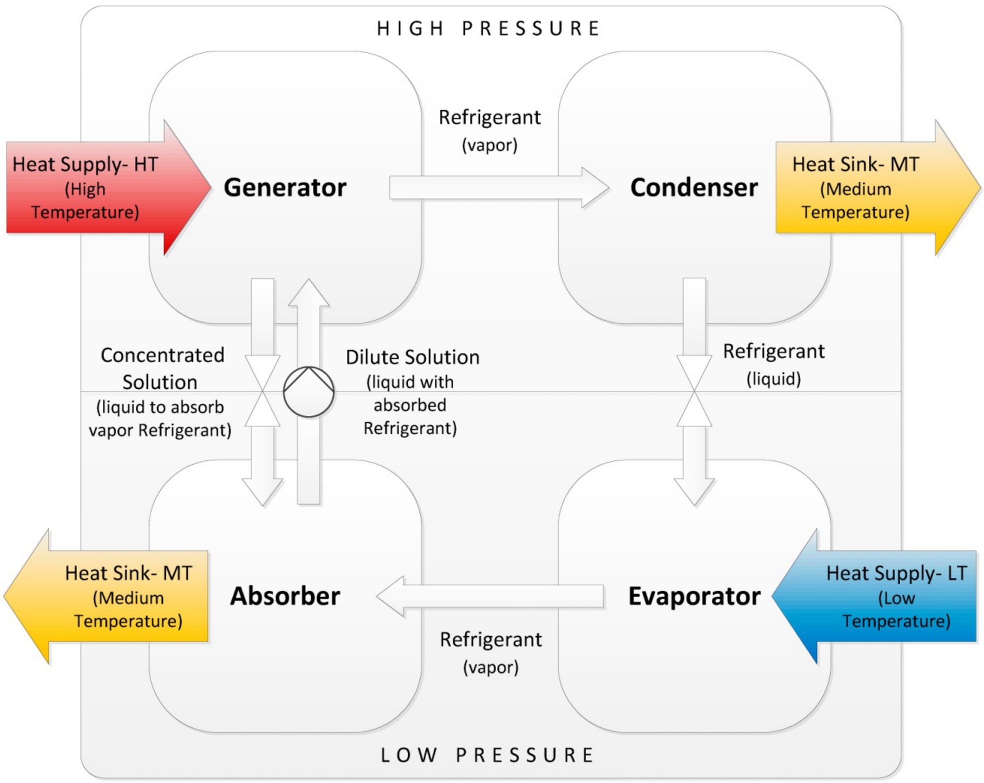


Figure 5-13: Abstract principle of absorption chiller

This is a simplified figure to illustrate the main principle clearly and to avoid over complication. Therefore, internal components such as the heat exchanger in the solution cycle between the generator and the absorber are not considered. Absorption chillers consist of four main components - the generator, the condenser, the evaporator and the absorber. Connections and piping between the components enable the circulation of the refrigerant water. While the generator and the condenser represent the high pressure areas, the evaporator and the absorber operate with lower pressure.

Starting with the absorption cycle, the liquid working pair lithium-bromide-water is pumped from the absorber to the generator. With heat at a high temperature (HT) from the thermal system, the refrigerant water is separated within the generator from the dilute solution via vaporization. Water vapor reaching the condenser is diluted by transporting the enthalpy of condensation to the environment via a medium temperature (MT) heat sink. Decreasing pressure between the condenser and the evaporator via an expansion valve, the refrigerant water turns from liquid to vapor phase. During phase changing within the evaporator, the refrigerant water draws heat from the low temperature (LT) heat supply. This effect is explained by the enthalpy of vaporization which leads to draw sensible heat from the connected cooling circuit. Closing the internal refrigerant circulation, the refrigerant vapor is liquefied via being absorbed from the concentrated lithium-bromide-solution within the absorber. Resulting from desorption within the generator, the solution returning to the absorber has a high rate of the sorbent lithium-bromide. The phase change of the refrigerant during the absorption process delivers heat (enthalpy of condensation) to be transported to the environment via the MT heat rejection system. The dilute solution, consisting of sorbent and absorbed refrigerant is pumped back to the generator enabling the next circle of the absorption process.

5.8.2 An ideal absorption cycle

For evaluating optimum operating conditions for sorption chillers, an ideal absorption cycle is considered following the theory delivered by Kaushik (Kaushik, Tomar & Chandra 1983). This solution is one of many, and is shown here because of calculating the COP from four temperatures as illustrated in Figure 5-13. However, in most cases $T_A = T_C$, assuming an ideal heat rejection. Recalling Figure 5-13 leads to Equation (5-23) for the energy statement of an ideal process, consisting of the heat flows crossing the system borders between the environment and the components generator, condenser, evaporator and absorber.

$$\sum_{in} \dot{Q} - \sum_{out} \dot{Q} = \dot{Q}_G - \dot{Q}_C + \dot{Q}_E - \dot{Q}_A = 0 \tag{5-23}$$

The general efficiency of sorption chillers is defined as the coefficient of performance (COP), calculated as the ratio of low temperature heat supply (cooling load) to high temperature heat supply (heat supply):

$$COP_{th} = \frac{Q_E}{Q_G} \tag{5-24}$$

Regarding the second law of thermodynamics, leads to the entropy balance given with Equation (5-25).

$$\sum_{in} \dot{S} - \sum_{out} \dot{S} = \frac{\dot{Q}_G}{T_G} - \frac{\dot{Q}_C}{T_C} + \frac{\dot{Q}_E}{T_E} - \frac{\dot{Q}_A}{T_A} = 0 \tag{5-25}$$

Equation (5-25)rearranged yields

$$\frac{\dot{Q}_G}{T_G} + \frac{\dot{Q}_E}{T_E} = \frac{\dot{Q}_C}{T_C} + \frac{\dot{Q}_A}{T_A} \tag{5-26}$$

Following the theory of an Ideal absorption cycle delivered by Kaushik (Kaushik, Tomar & Chandra 1983) leads to an absorption cycle via a reversible heat engine combined with a reversible heat pump. Whereby the heat engine consists of the generator and the absorber, and the heat pump operates between the evaporator and the condenser. Deduced from this configuration, the entropy reduction within the condenser is equal to the entropy gain in the evaporator, leading to an equivalent behavior while regarding the generator and the absorber also [see Equation (5-26)]. Combining those findings with the energy and entropy statement leads to the wide spread definition of the ideal COP expressed via temperatures:

$$COP_{th} = \left(\frac{T_G - T_A}{T_G}\right)\left(\frac{T_E}{T_C - T_E}\right) \tag{5-27}$$

From correlations operating an absorption cycle given by Equation (5-27), characteristics for increasing the COP are deduced via Equations (5-28).

$$
\begin{aligned}
COP_{th} &\propto \left(\frac{T_G - T_A}{T_G}\right)\left(\frac{T_E}{T_C - T_E}\right) \\
\Rightarrow\uparrow \left(\frac{T_G - T_A}{T_G}\right) &\cdot\uparrow \left(\frac{T_E}{T_C - T_E}\right) = \uparrow COP_{th} \\
\Rightarrow\uparrow T_G \wedge \downarrow T_A &\wedge \downarrow T_C \wedge \uparrow T_E \ \Rightarrow \uparrow COP_{th}
\end{aligned}
\tag{5-28}
$$

Hereby, increasing temperatures within the generator and the evaporator, as well as decreasing absorber and condenser temperatures, leads to an increasing COP for an ideal absorption cycle. Within the following section the basic conditions regarding an ideal process are transferred to market available sorption chillers.

5.8.3 Interfaces for integrating sorption chillers within thermal systems

For generic design, characteristics of common sorption chiller units have to be combined with theoretical thermodynamic rules for integrating with good system design. Figure 5-14 illustrates an abstracted model of an absorption chiller with heat flow interfaces.

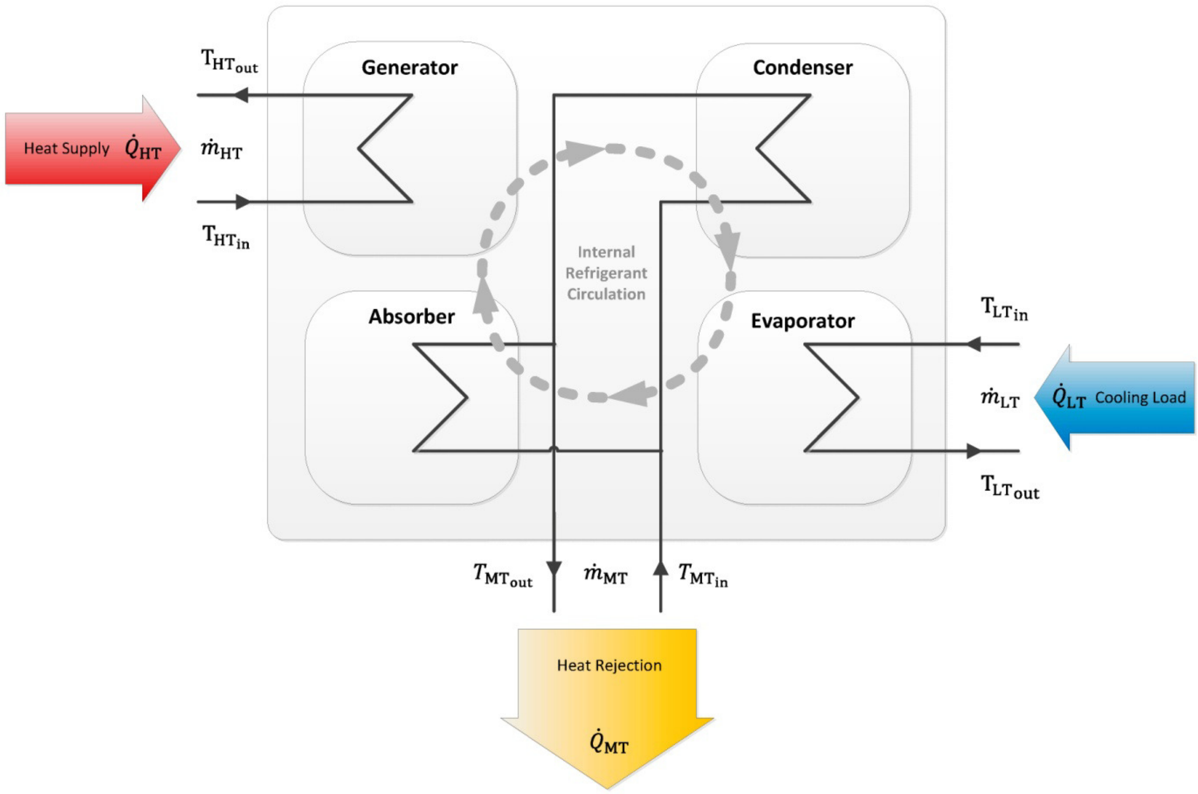


Figure 5-14: Chiller interfaces for system integration

For transporting the heat flows, each of the four components - generator, condenser, evaporator and absorber – is equipped with a heat exchanger. The high temperature heat (HT) for generating vapor refrigerant is supplied via a connected storage tank charged by various heat sources. The evaporator, connected to a cold storage draws sensible heat from the chilled circuit, covering the cooling load. In contradiction to the theoretical thermodynamic examinations from Kaushik (Kaushik, Tomar & Chandra 1983), the absorber and the condenser are not separately connected to heat sinks, but are combined to link the heat flow to one heat rejection system (assuming Ta = Tc = T_{MT}). To connect those heat exchangers in parallel is a common principle for market available units. Applying the ideal absorption cycle to the sorption chiller model delivers the energy balance given by equation (5-29).

$$\sum_{in} \dot{m}h - \sum_{out} \dot{m}h = \dot{Q}_{HT} + \dot{Q}_{LT} - \dot{Q}_{MT} = 0 \qquad (5\text{-}29)$$

Rearranging Equation (5-29), delivers a quite simple correlation between the heat flows:

$$\dot{Q}_{HT} + \dot{Q}_{LT} = \dot{Q}_{MT} \qquad (5\text{-}30)$$

The efficiency of sorption chillers is defined as the ratio of cold production to heat supply for driving the sorption process. The COP is illustrated in Equation (5-31).

$$COP_{th} = \frac{Q_{LT}}{Q_{HT}} < 1 \qquad (5\text{-}31)$$

Using Equation (5-27) yields Equation (5-32) for calculating the COP from temperatures.

$$COP_{th} = \left(\frac{T_{HT} - T_{MT}}{T_{HT}}\right)\left(\frac{T_{LT}}{T_{MT} - T_{LT}}\right) \qquad (5\text{-}32)$$

Equations (5-33) show the deduced characteristics for increasing the COP.

$$COP_{th} \propto \left(\frac{T_{HT} - T_{MT}}{T_{HT}}\right)\left(\frac{T_{LT}}{T_{MT} - T_{LT}}\right) \qquad (5\text{-}33)$$

$$\Rightarrow\uparrow\left(\frac{T_{HT}-T_{MT}}{T_{HT}}\right)\cdot\uparrow\left(\frac{T_{LT}}{T_{MT}-T_{LT}}\right)=\uparrow COP_{th}$$

$$\Rightarrow\uparrow T_{HT}\wedge\downarrow T_{MT}\wedge\uparrow T_{LT}\ \Rightarrow\uparrow COP_{th}$$

With increasing temperatures for HT and LT heat supply and a decreasing temperature of the MT heat sink, the COP for an ideal absorption process is increased.

In summary, there exist concise dependencies between the temperatures as well as between the heat flows for designing HT, LT and MT interfaces of the chiller.

5.8.4 EGM for operating integrated sorption chillers

For identifying more detailed characteristics for good operation of integrated sorption chillers, the method of entropy generation minimization is applied for evaluating the operation of real machines. Figure 5-15 illustrates the relevant thermodynamic model for operating a sorption chiller as an open system in steady state.

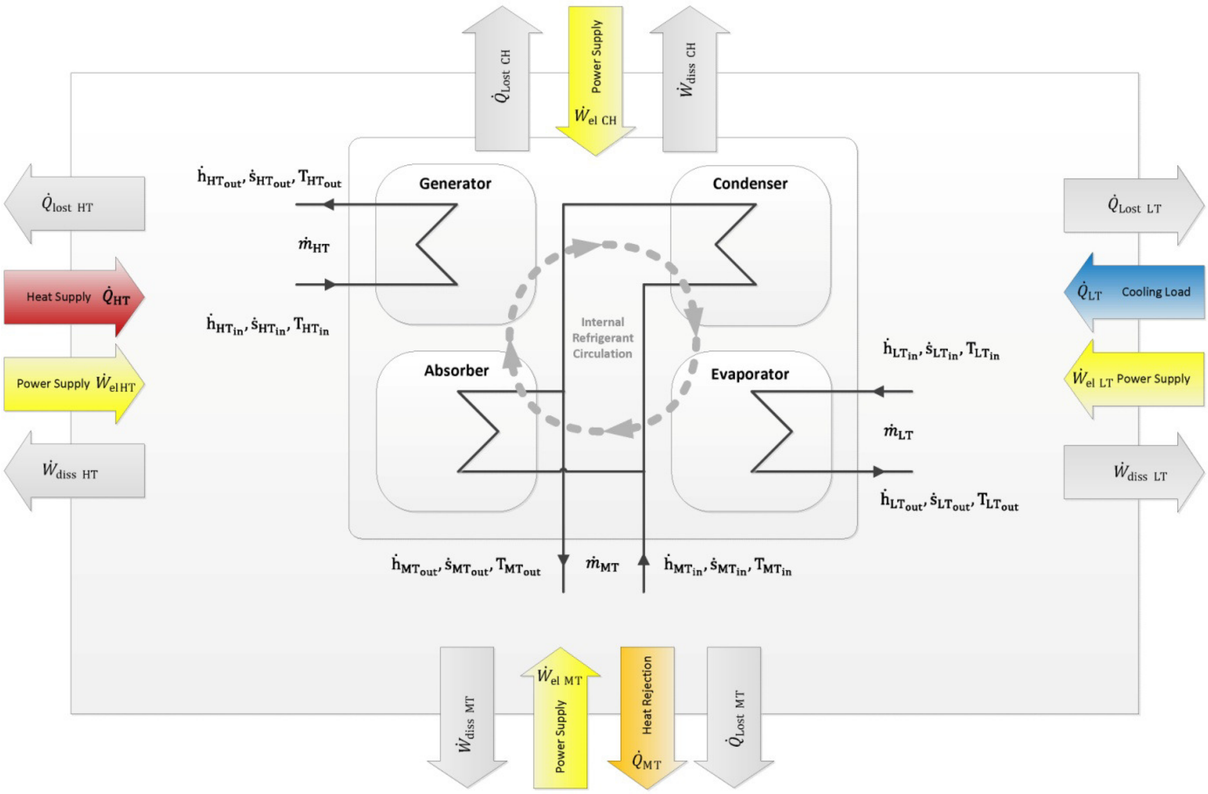


Figure 5-15: Thermodynamic model of sorption chiller

The model provides six ports for mass transfer, including one supply flow and one return flow for each interface (HT, LT, MT). It is premised that each interface as well as the chiller needs a power supply to provide mass flows and the operation of internal electric drives and controls. The irreversible operation of the system generates heat losses and technical work losses such as from fluid friction or heat transfer. For operating internal electric drives, pumps and controls, electric energy enters the system. Emerging irreversibilities resulting from heat losses, fluid friction and lost technical work while operating the real machine leave the system via dissipated power rates. The energy balance is described via the first law of thermodynamics in Equation (5-34), while combining dissipated work rates with lost heat rates to irreversible power.

$$\begin{aligned}\sum_{in}\dot{Q} - \sum_{out}\dot{Q} + \sum_{in}\dot{W} - \sum_{out}\dot{W} &= 0 \\ &= \dot{Q}_{HT} + \dot{Q}_{LT} - \dot{Q}_{MT} + \sum \dot{W}_{el} - \sum \dot{Q}_{lost} - \sum \dot{W}_{diss} \\ &= \dot{Q}_{HT} + \dot{Q}_{LT} - \dot{Q}_{MT} + \dot{W}_{el\,sys} - \dot{E}_{irr}\end{aligned} \tag{5-34}$$

Rearranging Equation (5-34) yields the irreversible power described via the specific heat transfer rates and the overall electrical power consumption:

$$\dot{E}_{irr} = \dot{Q}_{HT} + \dot{Q}_{LT} - \dot{Q}_{MT} + \dot{W}_{el\,sys} \tag{5-35}$$

Applying the second law of thermodynamics delivers the entropy balance of the regarded system:

$$\sum_{in}\dot{m}s - \sum_{out}\dot{m}s - \sum_{out}\frac{\dot{Q}}{T} + \dot{S}_{gen} = 0 \tag{5-36}$$

Assuming that dissipated work rates are converted to heat rates, yields Equation (5 – 37) for the entropy generation rate.

$$\dot{S}_{gen} = \frac{\dot{E}_{irr}}{T_0} + \sum_{in}\dot{m}s - \sum_{out}\dot{m}s \tag{5-37}$$

Equation (5–35) substituted into Equation (5–37) delivers Equation (5-38).

$$\dot{S}_{gen} = \frac{1}{T_0}\left(\dot{Q}_{HT} + \dot{Q}_{LT} - \dot{Q}_{MT} + \dot{W}_{el\,sys}\right) + \left(\sum_{in} \dot{m}s - \sum_{out} \dot{m}s\right) \qquad (5\text{-}38)$$

As shown by Equations (5–37) and (5-38), the entropy generation rate of the system is described via a ratio irreversible power to the ambient temperature, plus the sums of specific entropy changes resulting from mass flows. Considering that the specific entropy changes (right side of Equation (5-39)) result from controlling the operation of the chiller (left side of Equation (5-39)), makes clear that despite of specific chiller performance characteristics, entropy generation of the system is a result of adjustable conditions such as temperatures, mass flows and the power consumption of electrical components.

$$\dot{S}_{gen} = \frac{1}{T_0}\left(\dot{m}_{HT}\Delta h_{HT} + \dot{m}_{LT}\Delta h_{LT} - \dot{m}_{MT}\Delta h_{MT} + \dot{W}_{el\,sys}\right) + \left(\sum_{in} \dot{m}s - \sum_{out} \dot{m}s\right) \qquad (5\text{-}39)$$

Reducing entropy generation implies decreasing the products of HT and LT mass flows with their specific enthalpy differences as well as decreasing the electric power consumption and increasing, or preserving the specific MT product of the term. When decreasing HT and LT mass flows, the electrical power rate for driving the pumps is automatically reduced as well. However, achieving good results from varying mass flows of the sorption chiller (HT, MT, LT), strongly depends on the specific internal design of heat transfer components.

In general, the dependencies from varying mass flows have to be respected through good design of the chiller unit as well as by optimized integration within an overall system.

The findings from focusing on entropy generation and recalling the principles for increasing the COP, lead to control of the mass flows at the HT and LT interfaces while maintaining the temperature demand for an efficient sorption process.

This strategy is compliant with results from Wijesundera (1996), describing the correlation between maximum cooling capacity and the COP, whereby a reduced cooling performance leads to a higher efficiency. Within the following section, the causes for entropy generation are transferred to EGM-characteristics for specifying optimum operation conditions for sorption chillers.

5.8.5 EGM characteristics for optimized operation of sorption chillers

As mentioned before, identified EGM-characteristics for efficient chiller operation are highly influenced by the specific design of each sorption chiller. Beside optimum integration, the machines have to be chosen with consideration for the EGM characteristics. Table 5-8 illustrates the causes for entropy generation with deduced specifications for hydraulics and control.

Table 5-8 Transfer of design characteristics for EGM to design specifications for integrating sorption chillers

Causes for Entropy generation $\dot{S}_{gen}$	Design characteristics for EGM $\downarrow \dot{S}_{gen}$	Specifications for Integrating sorption chillers A. Hydraulic specification B. Control specification
Heat transfer via external heat exchangers and internal refrigerant circulation causing e.g. fluid friction, heat losses, dissipation…	1. Reduce mass flow of HT and LT interface for maximum ΔT_{HT} and ΔT_{LT} considering specific ranges given by sorption chiller	A. Hydraulics Ensure good piping design for low pressure drops and sufficient mass flow for HT and LT heat supply. B. Control Provide target temperature control for maximum temperatures, and temperature difference control for increasing $\Delta T_{HT}, \Delta T_{LT}$
	2. Keep high mass flow of MT interface for minimum ΔT_{MT} considering specific ranges given by sorption chiller	A. Hydraulics Ensure good piping design for low pressure drops and sufficient mass flow for MT heat sink B. Control Provide target temperature control for minimum temperatures, and temperature difference control for decreasing ΔT_{MT}
Consumption of electricity for operating the sorption chiller and providing sufficient mass flows for the interfaces HT, LT and MT	1. Reduce power consumption of internal and external electric drives, pumps, fans and controls	A. Hydraulics Ensure a low number of actuators for the chillers interfaces. B. Control Provide high efficient components with interfaces for speed control (HT, LT and MT). Optimize heat rejection system for minimum power consumption. Implement demand oriented control for operating all components for cold production for reduced operating times

Summarizing deduced operation conditions leads to contradictions between good design for sorption chillers and good design of the connected thermal system (see Table 5-9). Compared with common mass flows for heat generation, the mass flows required for supplying sorption units are much higher, having caused various shortcomings and inefficient operation for previous cooling systems.

Table 5-9: Contradictory characteristics for integrating sorption chillers

Interface of Sorption chiller	Characteristics for good operation of sorption chillers	General Characteristics for good operation of thermal systems
Heat Rejection (MT)		
Mass flow (MT)	**HIGH** Mass flow must be sufficient high for good heat exchange and low dT for internal heat transfer process	**LOW** Mass flow should be low for low pressure drops and low consumption of electricity
Inlet Temperature (MT) and dT	**LOW** Inlet Temperatures from heat rejection system must be low for high efficiency $\downarrow T_{MT} \Rightarrow \uparrow COP_{th}$ $\downarrow \Delta T_{MT} \Longrightarrow \downarrow \dot{S}_{gen}$	**HIGH** The inlet temperatures depend on the specific heat rejection system, application and geographical location. In most cases, providing a higher inlet temperature and a higher dT cause less effort for energy and ressources
Cooling load (LT)		
Mass flow (LT)	**HIGH** Mass flow must be sufficient high for good heat exchange and internal heat transfer process	**LOW** Mass flow should be low for low pressure drops and low consumption of electricity
Inlet Temperature (LT) and dT	**HIGH** Inlet Temperatures from cooling load should be increased for high efficiency $\uparrow T_{LT} \Rightarrow \uparrow COP_{th}$ $\uparrow \Delta T_{LT} \Longrightarrow \downarrow \dot{S}_{gen}$	**HIGH - LOW** The inlet temperatures depend on the specific cooling application. Providing a higher inlet temperature and a higher dT lead to less energy effort, but also in many cases leads to a higher financial effort for cold distribution (e.g. larger heat exchangers)
Heat Supply (HT)		
Mass flow (HT)	**HIGH** Mass flow must be sufficient high for good heat exchange and internal heat transfer process	**LOW** Mass flow should be low for low pressure drops and low consumption of electricity

Inlet Temperature (HT) and dT	**HIGH** Inlet Temperatures from heat supply load should be increased for high efficiency $\uparrow T_{HT} \Rightarrow \uparrow COP_{th}$ $\uparrow \Delta T_{HT} \Longrightarrow \downarrow \dot{S}_{gen}$	**HIGH-LOW** The provided inlet temperatures depend on the specific heat generation units. Providing a higher inlet temperature leads to more energy effort. Providing a higher dT lead to less energy effort. Common heat generation units have provide a much higher dT than demanded by the sorption chiller.

During design, appropriate methods for integration have to be applied to harmonize heat and cold generation of the system.

5.8.6 Specification of cold generating components

Combining EGM-characteristics and optimum operating conditions for cold generating components with good thermal system design characteristics leads to specification of integrated cooling components (see Table 5-10).

Table 5-10: Specifications for integrated cooling components

Requirements (for good operation of thermal components)		**Specifications for Integrated cooling components** Operation with novel system architecture including - **target-temperature-control** - **hydraulic separation via thermal storages (HT and LT)** - **best specific operating conditions**
1. Durability and Reliability	**a) Operation with low wear**	☑ **YES** Few start-stop periods with long operation times leads to low wear.
	b) Protection against overheating/ freezing	☑ **YES** Integrated protection against freezing through onboard and system control (chiller and heat rejection system)
	c) Supply guarantee	☑ **YES** Communication of heat demand to provide sufficient cooling load; Redundancy via various heat sources and providing peak load chiller function

2. Efficiency	**a) High thermal efficiency during operation**	☑ **YES** High efficiency through optimized heat supply (sufficient supply temperature with sufficient mass flow). Low heat losses via short piping length
	b) Low Standby-losses	☑ **YES** Low standby losses through short start-up phases, long and steady operation times and short shut-down phases
	c) Low Pressure drops	☑ **YES** A low number of hydraulic elements, combined with good hydraulic design leads to low pressure drops
	d) High capacity factor for direct usable heat	☑ **YES** High capacity factor for direct usable heat resulting from target-temperature control and optimized hydraulics
	e) Low consumption of fossil resources	☑ **YES** Low consumption of fossil energy resources because of integrated priority for renewable sources for thermal supply. Low consumption of electricity through low pressure drops, efficient electric components and speed control for pumps and fans (chiller and heat rejection system)
3. Synergies for improved operation	**a) Additional Components for synergies**	☑ **YES** The cold storage tank allows cold generation, even if not demanded, enabling efficient and hydraulic separated mass flow
	b) Synergies for Coordination	☑ **YES** Easy coordination because of Target-temperature-control and hydraulic separation
	c) Synergies for other Components	☑ **YES** The cold storage improves the efficiency of the solar thermal plant, as heat surplus can be used for cold generation
4. Hydraulics and Coordination	**d) Good coordination of involved components**	☑ **YES** Good coordination of involved components for cold generation via system control, enabling target-temperature control and demand orientation

e)	**Good Hydraulic connections**	☑ **YES** Easy and efficient piping for heat supply and cooling load via connected storage tanks. A low number of involved components for determined operation conditions
f)	**Good Control interfaces**	☑ **YES** System control for good coordination and providing target-temperature-control for dynamic demand oriented cold generation

With specifying components for cold generation, the premises for good overall system design are given. Within the next chapter, generic design of solar cooling system is described.

5.9 Generic design of integrated thermal system components

Based on developed system architecture and specifications from previous sections, integrated components are designed via market-available elements for control and hydraulics. Following the GLD-method, a model for demand-oriented operation of sorption chiller systems was developed to evaluate the required temperature set points for each component involved (see Figure 5-16 for abstracted logic example).

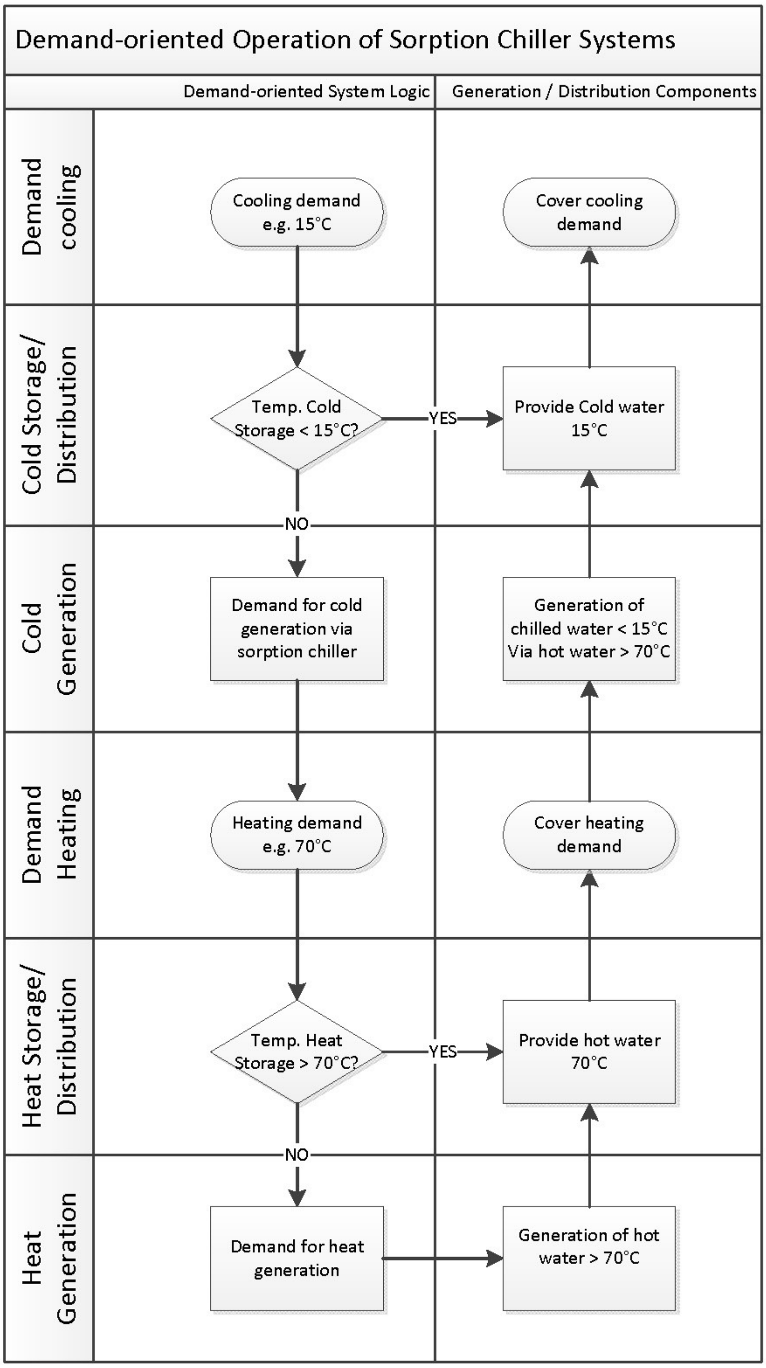


Figure 5-16: Demand-oriented operation of sorption chiller systems (logic example)

5.9.1 Bottom-up generic design via design elements

Following the theory of nested systems, having completed the top-down specification from upper-level systems down to the lower-level system consisting of components and parts, the generic design is processed bottom-up starting with the lower-level systems (see Figure 5-17). With generic components, subsystems are formed leading to an integrated overall thermal system, including previous investigated findings and characteristics for optimized system design.

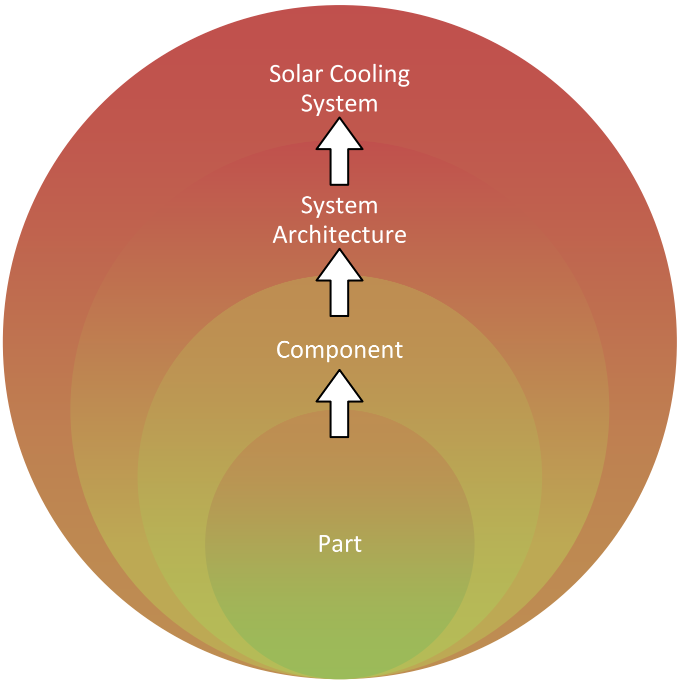


Figure 5-17: Model of Nested systems – Bottom-up generic design via design elements

Regarding the system architecture for hydraulics and control from sections 5.3.1 and 5.3.2, components specified are designed. Via market available parts consisting of hydraulic and control elements, generic components for creating a solar cooling system are developed within the following sections.

5.9.2 Integrated design of thermal storage

Having a central role within the thermal system, the heat storage component is designed first. Summarizing specifications for this components leads to a generic storage tank design illustrated in Figure 5-18.

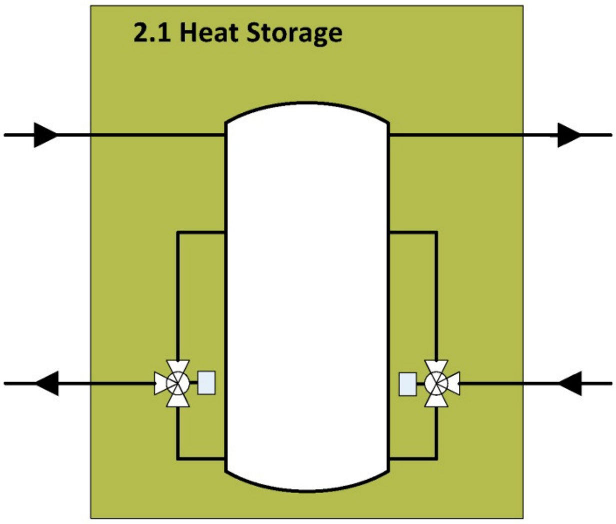


Figure 5-18: Design of thermal storage

Enabling hydraulic separation and the priority for renewables, the charging and discharging strategy was optimized via the EGM-method, confirming target-temperature control for optimized operation. To implement the investigated results, the storage tank is equipped with two valves for dynamic operating volumes. Depending on the charging level, either the small volume (upper part of the tank), or the whole tank is activated. Via one valve for charging with heat and one independent valve for discharging, good efficiency of the storage is ensured during dynamic operation. Enabled via target-temperature control, the heat supply flow from generating units and the supply flow for heat demanding components are located on the top of the tank. In case of no intermittent heat generation from solar thermal systems, only the small upper part of the storage volume is activated, operating as a hydraulic switch for separating heat generating and demanding units. If solar energy is stored within the tank, the return flow on the discharging side is switched to the lower level for complete usage of solar gains. The principle for charging the tank is to provide involved generation units with differing charging volumes. Following the specifications for the priority of renewable sources, intermittent renewable sources can operate the whole volume. Biomass and CHP-units operate a smaller ratio, and peak load heat generation units only charge the top of the tank. Via this strategy, various heat source combinations can easily be implemented, always enabling independent and therefore redundant operation of each component resulting from hydraulic separation.

5.9.3 Integrated design of heat generation units

With the developed storage design, heat generation components are integrated applying given specifications. For generic design, each component is equipped with interfaces to connect with each other, forming subsystems which are compliant with the system architecture. Starting with solar thermal components delivers a subsystem including distribution elements as shown in Figure 5-19.

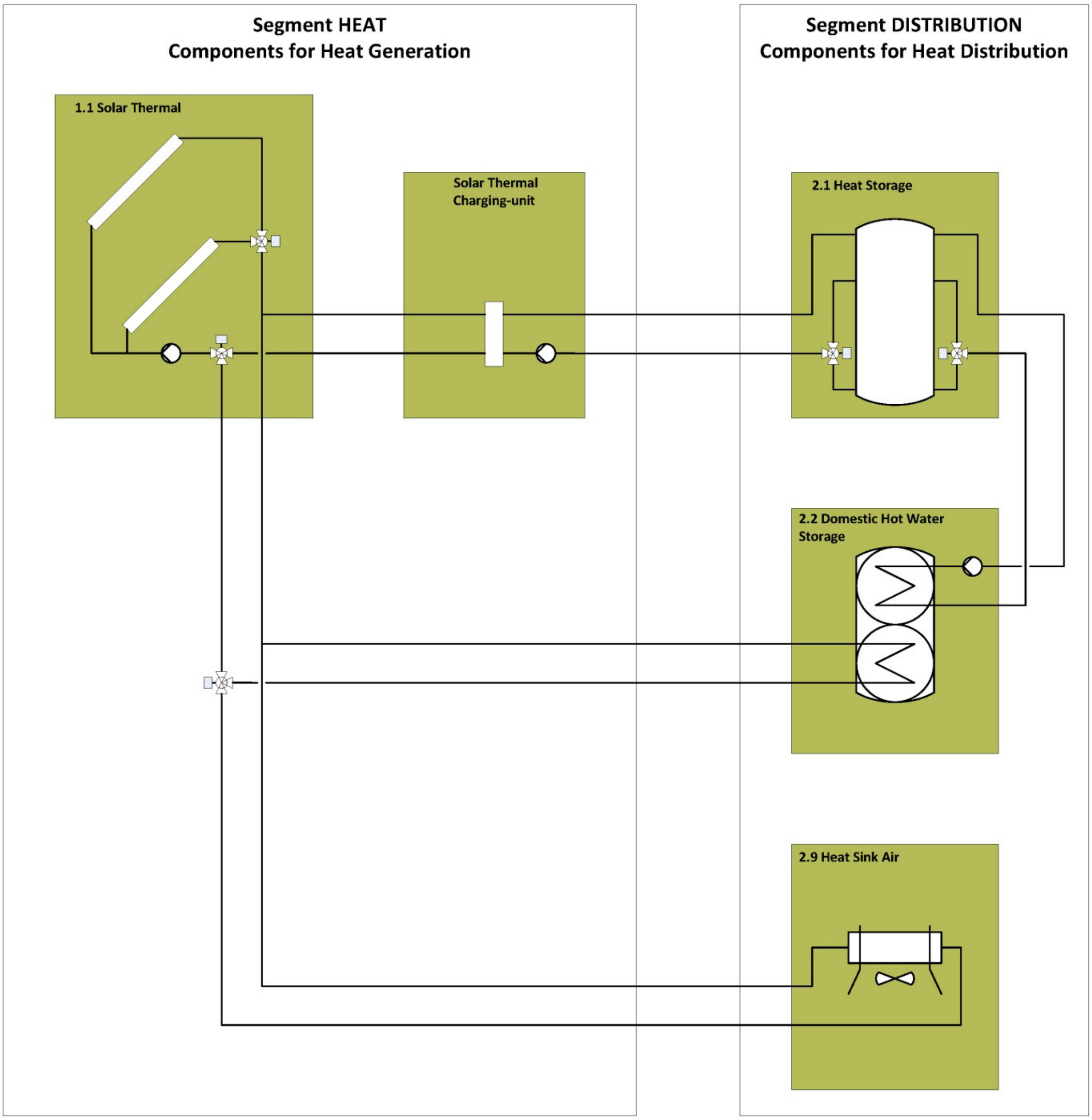


Figure 5-19: Integrated design of solar thermal components

Beneath the specific components, hydraulic and control assemblies such as the solar thermal charging unit are created, for easy implementation of the system configuration using the same modules for various applications. This strategy leads to a modular thermal energy system enabling an ongoing evolutionary optimization process, without having to reinvent the entire system. The solar thermal system shown in Figure 5-19 can supply three heat consumers, whereby the sequence is given by the individual application. Solar gains are used to charge a storage tank with target temperature, prepare domestic hot water and for example to heat up a pool. The third solar heat sink can alternatively be used for prevent overheating of the system, through installing a fluid-air heat exchanger as illustrated in Figure 5-19. For enabling efficient solar thermal heat generation even for systems with differing roof orientations or different integrated collector types, the operation of two solar thermal collector fields is provided. Beneath the direct preparation of domestic hot water, stored solar gains can be used via heat supply from the thermal storage. The same principle is applied for components generating heat from dispatchable sources (see Figure 5-20). These are units driven by fossil and renewable sources being controllable concerning to supply the system with heat. Those heat generation units are declared to be applicable for base load and/or peak load.

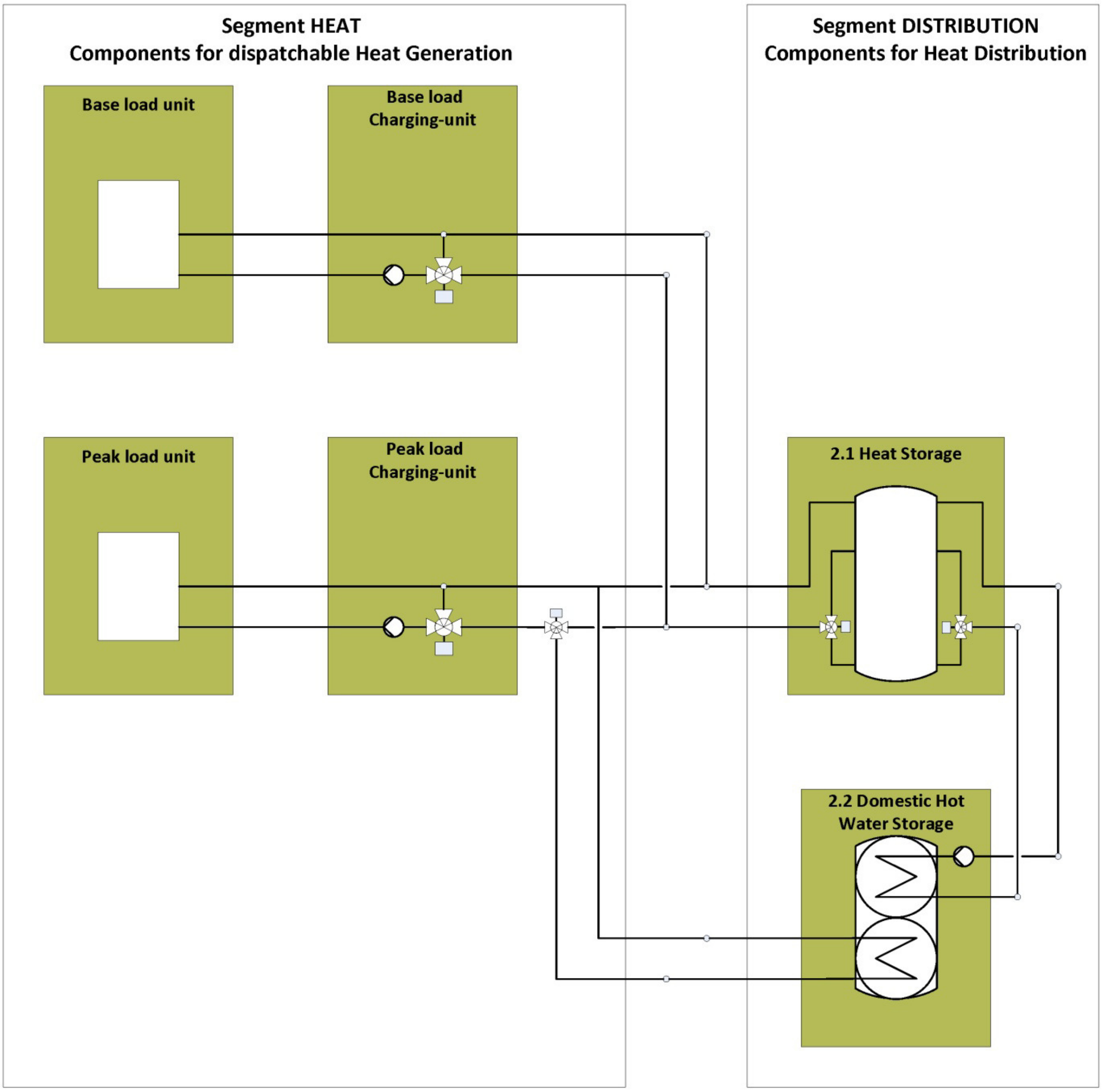


Figure 5-20: Integrated design of components for dispatchable heat generation

Suitable components for covering base loads are those which enable good results from long operation times and a low number of start-stop periods, such as biomass-fired boilers and CHP-units. For peak loads heat generation units should be able to deliver a dynamic performance for heat supply to prevent high wear and low efficiency. Following the priority for renewables, fossil driven heat sources such as oil or gas-fired boilers, should only be used for peak loads. Being able to integrate the high variety of heat generating units on the market, the modular thermal system provides different types of charging units illustrated in Figure 5-21.

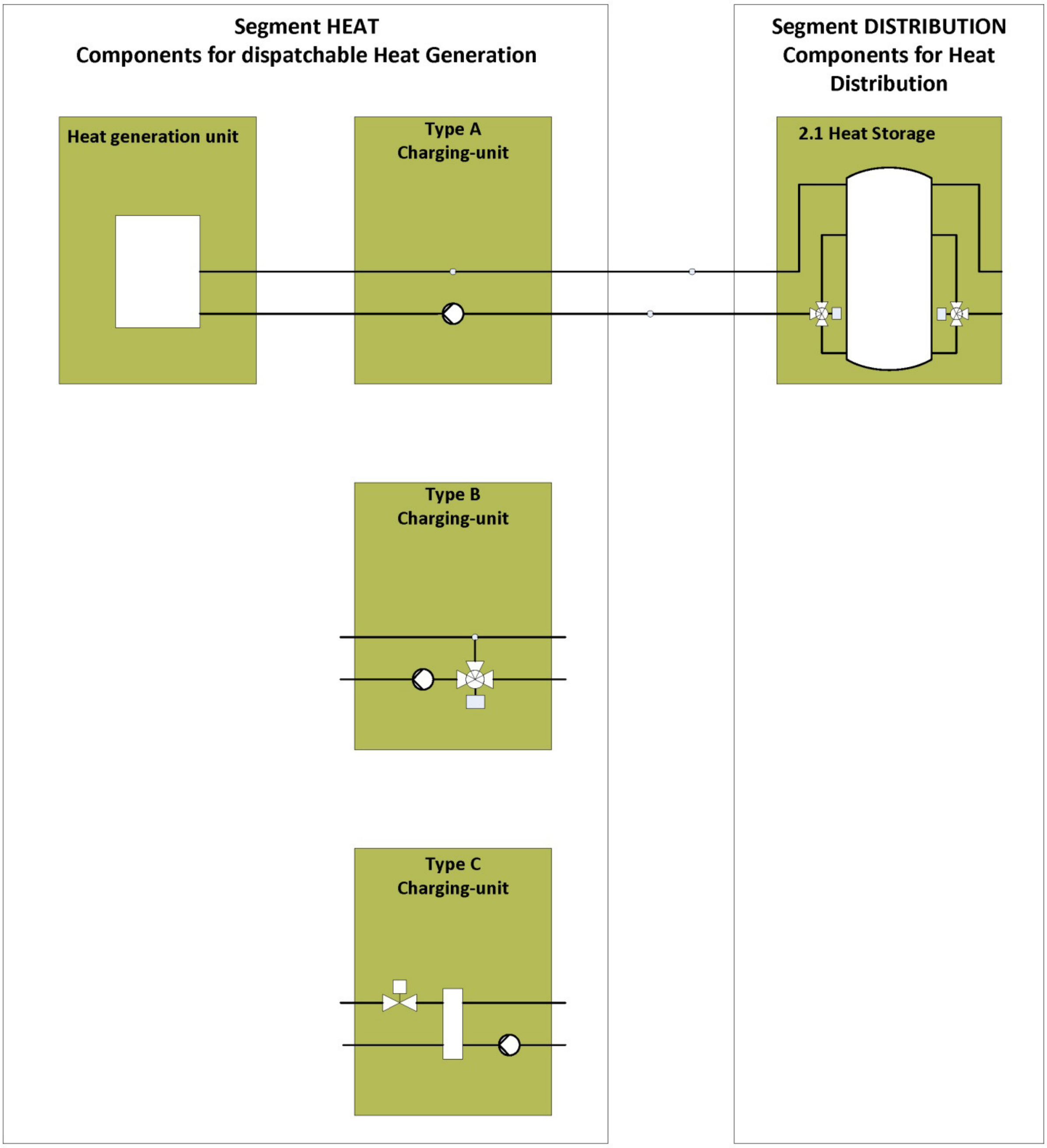


Figure 5-21: Alternative types of charging units for heat generation

With types A to C, various operation and control strategies can be implemented, including speed controlled mass flows, return flow boosts or hydraulic separation for e.g. district heating applications.

5.9.4 Integrated design of distribution units

The design of distribution components includes storages for heat and cold generation units, as well as heating, cooling and combined heating and cooling circuits (see Figure 5-22).

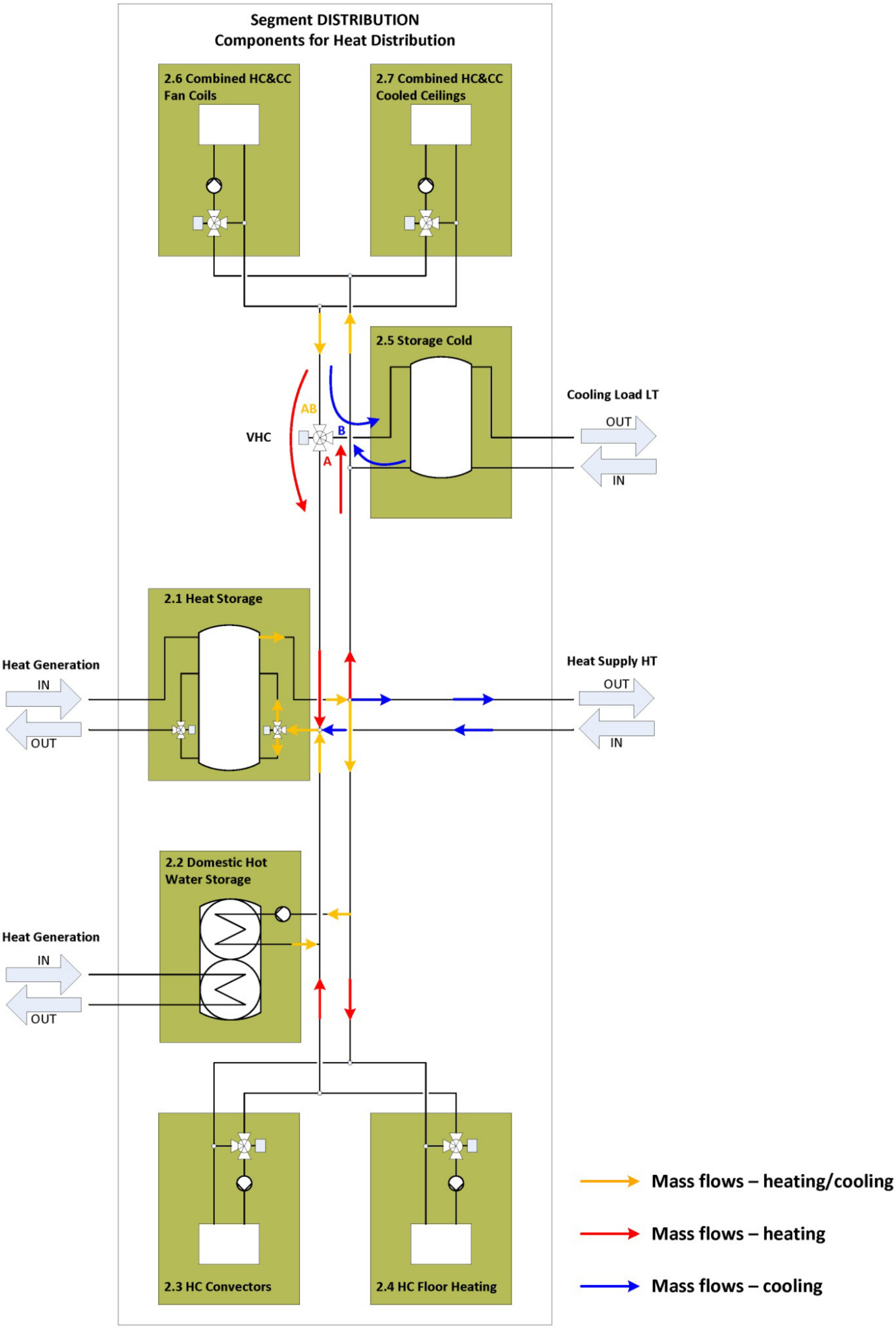


Figure 5-22: Integrated design of distribution components

The different mass flows depending on the operation modes heating, cooling and combined heating and cooling are shown to illustrate the different operation modes.

Via interfaces to the segments HEAT and COOLING, the resulting subsystem for distribution provides all market available methods for fluid based heat exchange to cover heating and cooling demand. The designed distribution circuits enable demand-oriented hot and chilled water supply for e.g. convectors, fan-coils, or floor heating systems. If suitable for heating and cooling, the circuit, for example, provides heat supply during winter, and cold supply for cooling in summer, enabled via switching from the heat storage tank to the cold storage (see valve VHC in Figure 5-22 using ports AB-A for heating and AB-B for cooling). Simultaneous heating and cooling of different rooms is provided via heat supply by the heating circuits (see bottom of Figure 5-22) and cold supply by the cooling circuits (see top of Figure 5-22). As for heat generation units, all hydraulic and actuator assemblies provide high efficient technologies such as speed controlled mass flows and demand-oriented supply-flow temperatures.

5.9.5 Integrated design of cold generation units

Following the modular structure for design, components for cold generation are illustrated in Figure 5-23. In addition to operating thermally driven sorption chillers, the operation of a peak load chiller as an alternative to a thermal back-up is provided by the system. In compliance to the priority for renewable sources, the solar driven sorption chiller is intended to cover base loads. Such a system might be a common application when extending existing compressor driven cooling system.

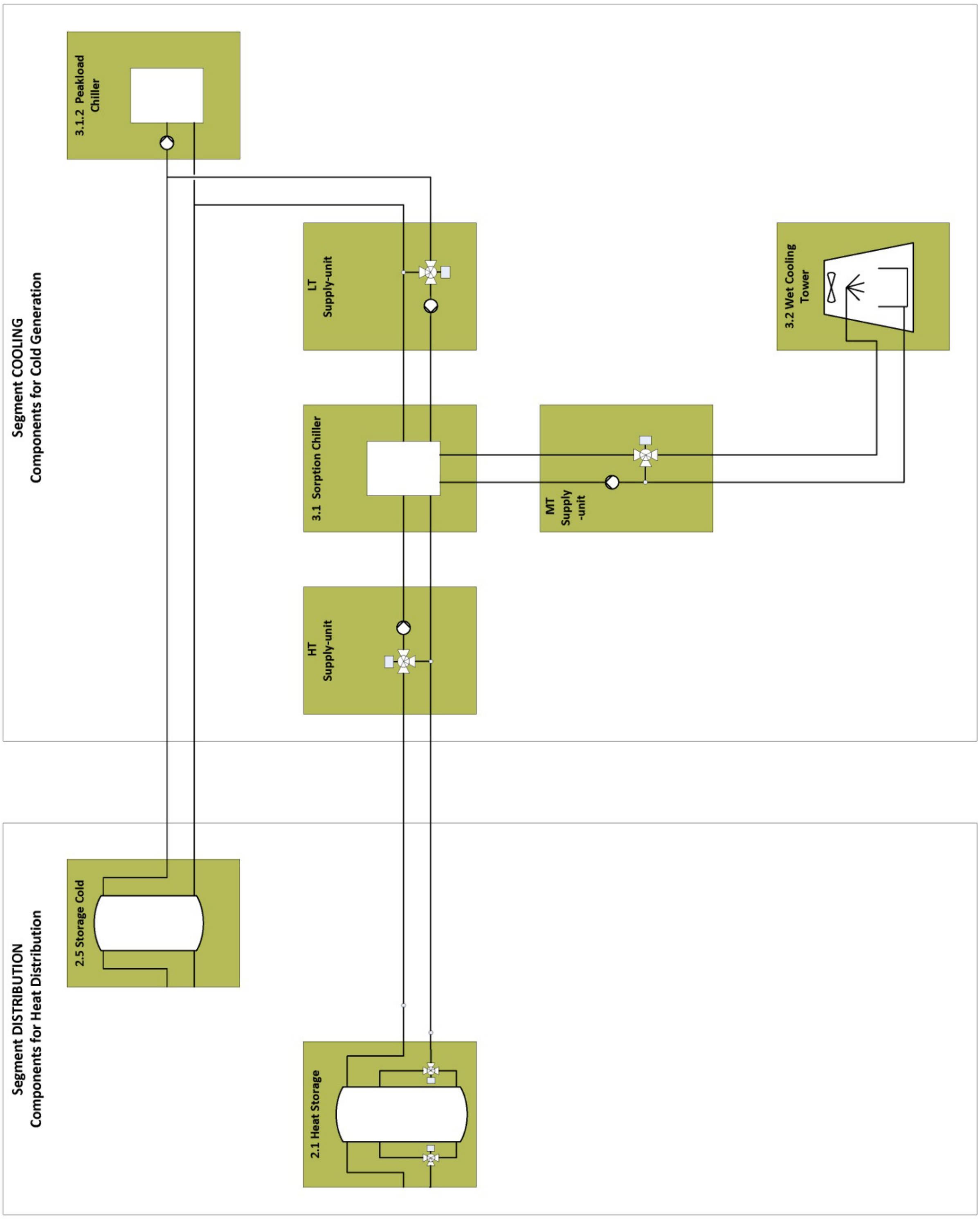


Figure 5-23: Integrated design of components for cold generation

Like other components before, several types of assemblies for supplying the sorption chiller interfaces are possible (see Figure 5-24). Enabling the operation of absorption and adsorption chillers as well as applications in differing climate zones, several heat rejection systems are supported. The MT heat sink for the sorption process can be implemented via a wet cooling tower, a dry cooler or via a user-defined heat sink. For separating the closed hydraulic system from an open heat rejection system, for example while combining an adsorption chiller with a wet cooling tower or for integrating any user-defined heat sink, the MT-circuit can also be operated with an external heat exchanger.

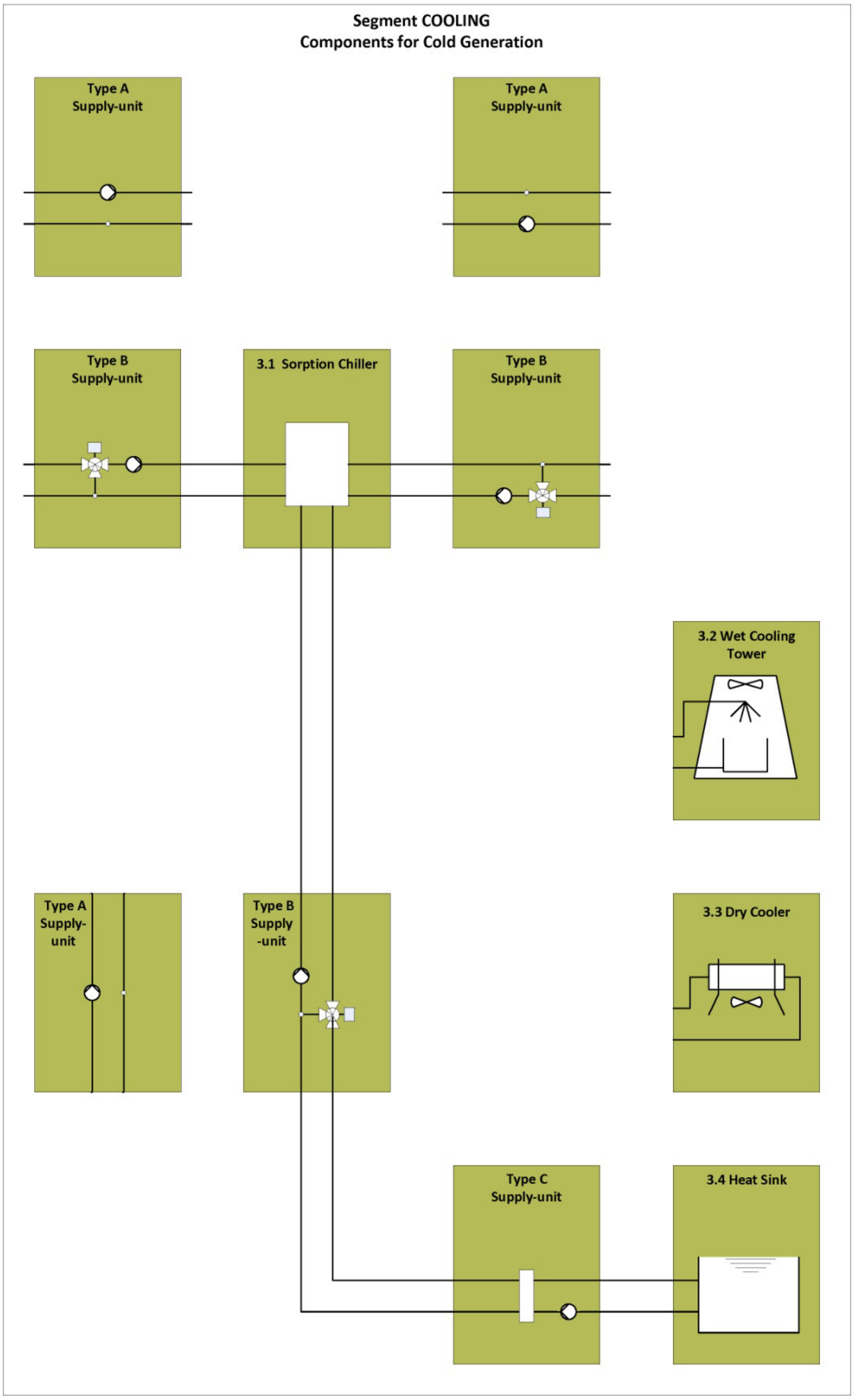


Figure 5-24: Alternative supply units and heat rejection systems for cold generation components

With generically designed components, the overall system for solar cooling can be created as described in the following section.

5.10 Applying generic design for solar cooling systems

The generic design of solar cooling systems described within this work is based on a modular thermal system, consisting of various components and subsystems. Designing an overall system, general principles and rules have to be defined while combining modules for specific applications. For this work, the synthesis of system architecture with integrated designed components is guided through applying target-temperature control and the central thermal storage, giving a basic configuration to ensure the intended function of the system.

5.10.1 Thermal system configurations

For solar cooling systems based on generic design elements, a minimum configuration is defined for further work. The challenge consists of keeping the advantages of various applications while always ensuring a basic functional structure. This is essential for product development, especially for designing the control system. Based on the basic intention of solar cooling, the minimum configuration consists of components for solar thermal heat generation, distribution components and components for cold generation (see Figure 5-25).

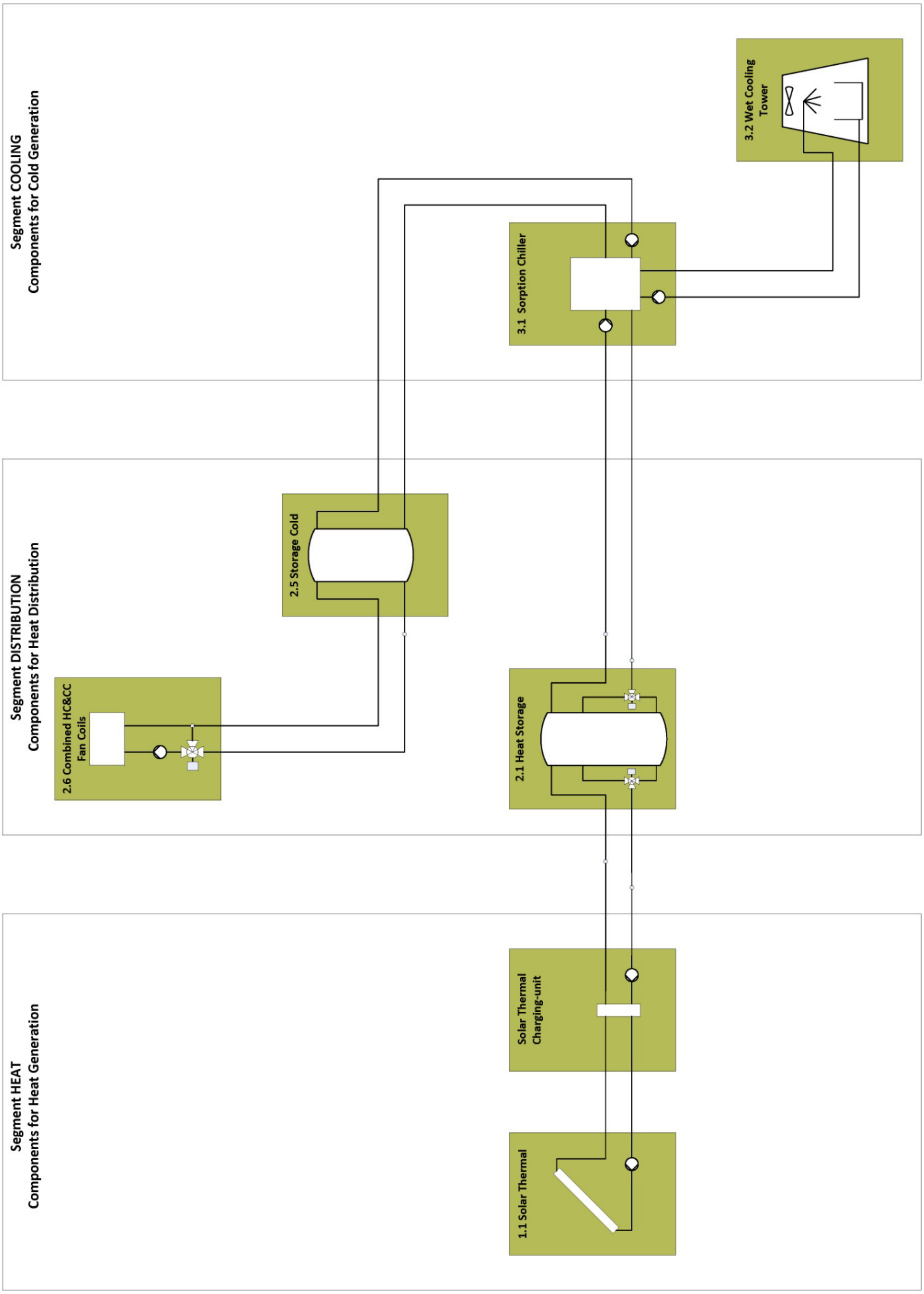


Figure 5-25: Minimum configuration of a solar cooling system

For the existing heating market, a configuration covering a good portion of all pure heating applications is illustrated in Figure 5-26. This version supports up to three heat generation units, including a solar thermal system, a base load heat source and one peak load unit to supply the domestic hot water preparation as well as the heating circuits. For distributing heat, up to four heating circuits are provided.

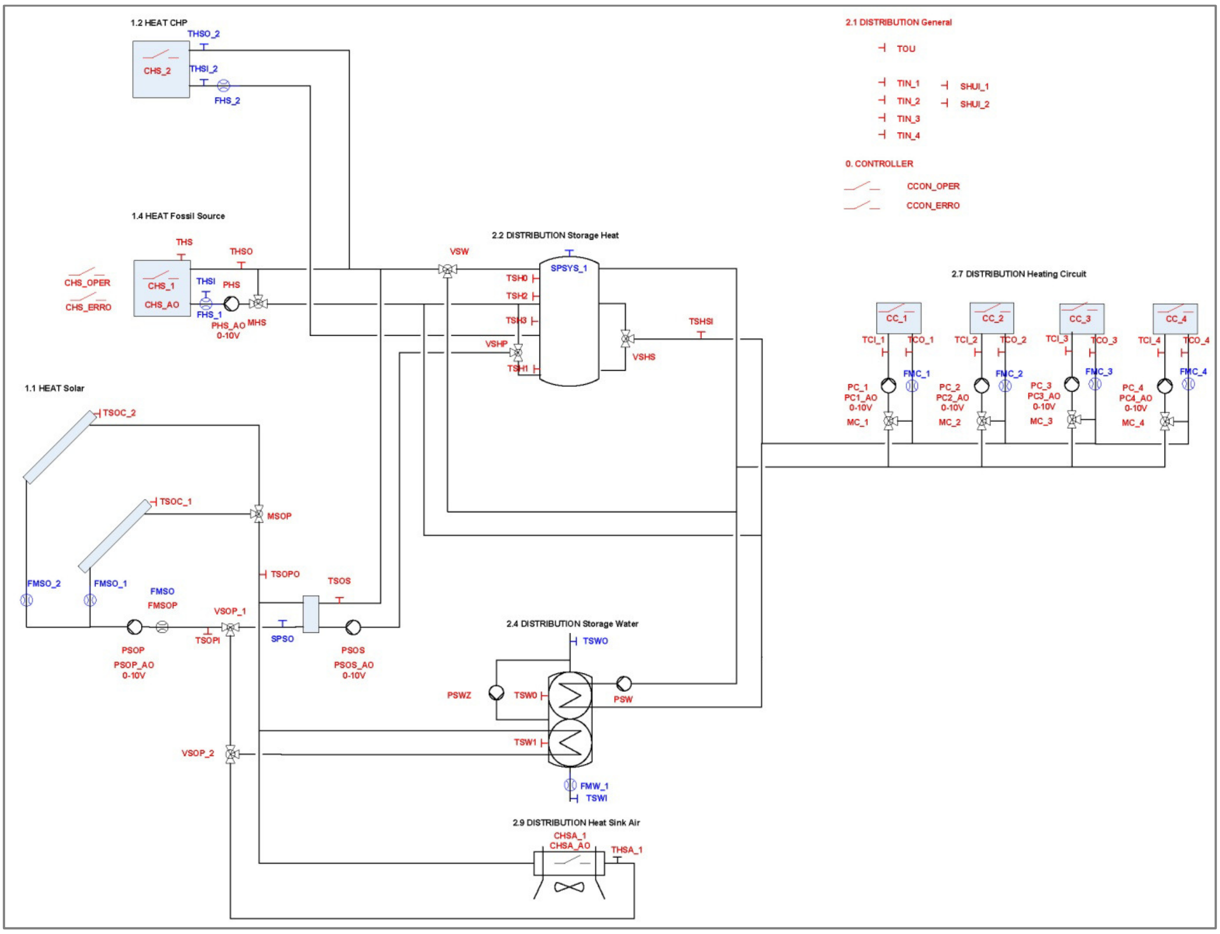


Figure 5-26: System configuration for pure heating applications

Entering the heating market with the product “solar cooling”, leads to configuration of a combined heating and cooling system as illustrated in Figure 5-27.

With Figure 5-26 and 5–30 being potential system configurations for entering the market, it is evident that it is necessary to develop missing elements for hydraulic and control implementation. Neither control systems nor integrated sorption chiller systems comparable with the developed configurations, are available on the market.

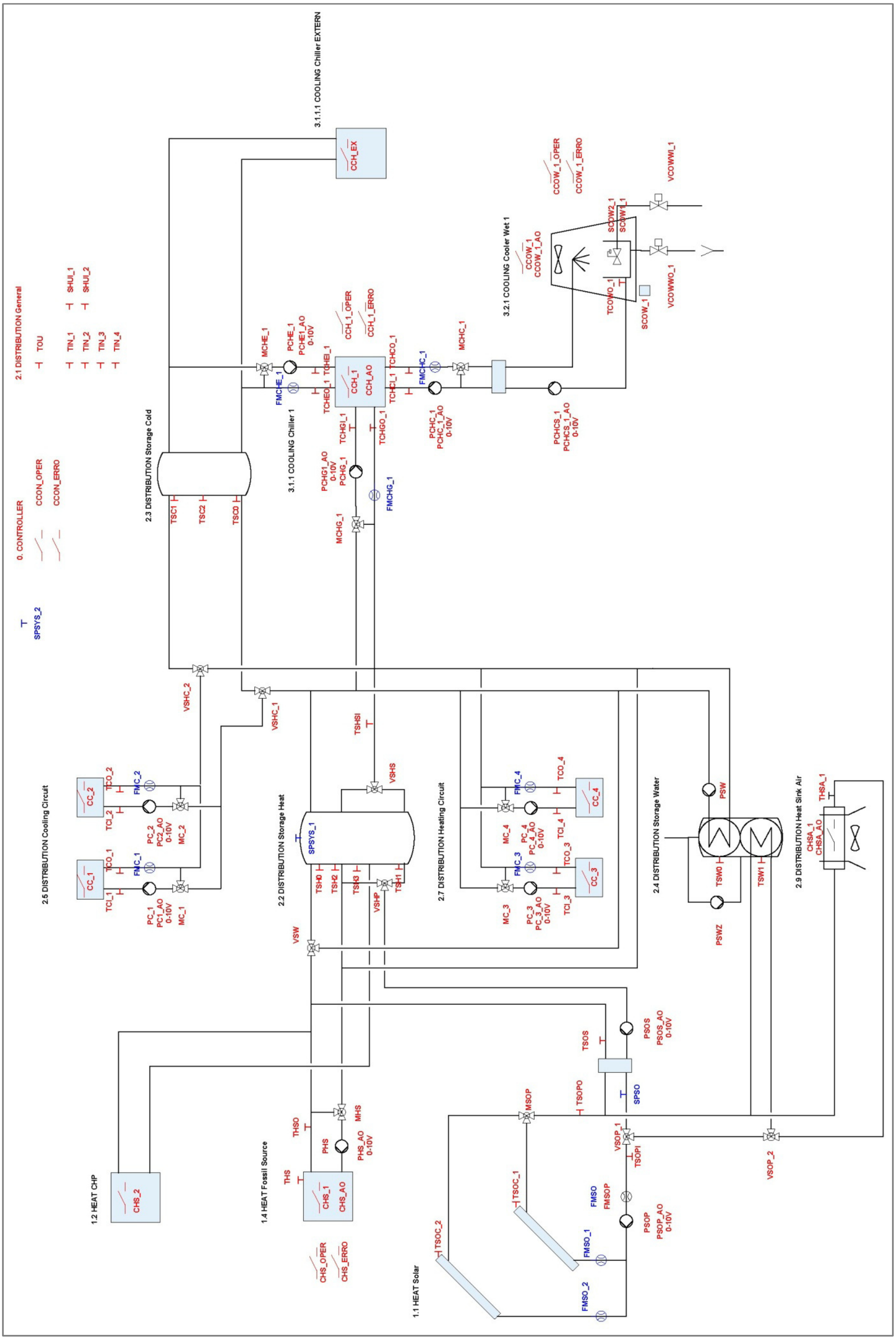


Figure 5-27: Solar cooling system including heating applications

5.11 Summary of generic design

This chapter has described the generic design of solar cooling systems guided by the theory of nested systems for concise and efficient work on holistic systems. With requirements from the analysis in chapter 4, applying novel methods such as the HDC-heat flow model and the GLD-method for optimized thermal design, concepts for hydraulics and controls have been developed. Following the theory of nested systems led to the implication that for good thermal system design, it is necessary to apply target temperature control combined with a central thermal storage. Via the method of entropy generation minimization, a better design was developed, leading to optimized specifications for heat generation and distribution components. Applying the EGM-method for optimum sorption chiller operation gave specifications for optimized integration of cold generation components. With completed specifications, the generic design phase was processed bottom-up, beginning with generic components for system integration and leading to system configurations for optimized solar cooling systems.

The applied methodology led to a modular thermal energy system enabling an ongoing evolutionary optimization process, without having to reinvent the entire system.

6. Implementation of a novel solar cooling system

6.1 Preamble

The purpose of this chapter is to describe the implementation of the investigated generic design for solar cooling systems. Firstly, the need for novel components and therefore the tasks for product development are clarified. Considering the market availability of the design elements involved for solar cooling systems, the requested product groups are illustrated in Figure 6-1.

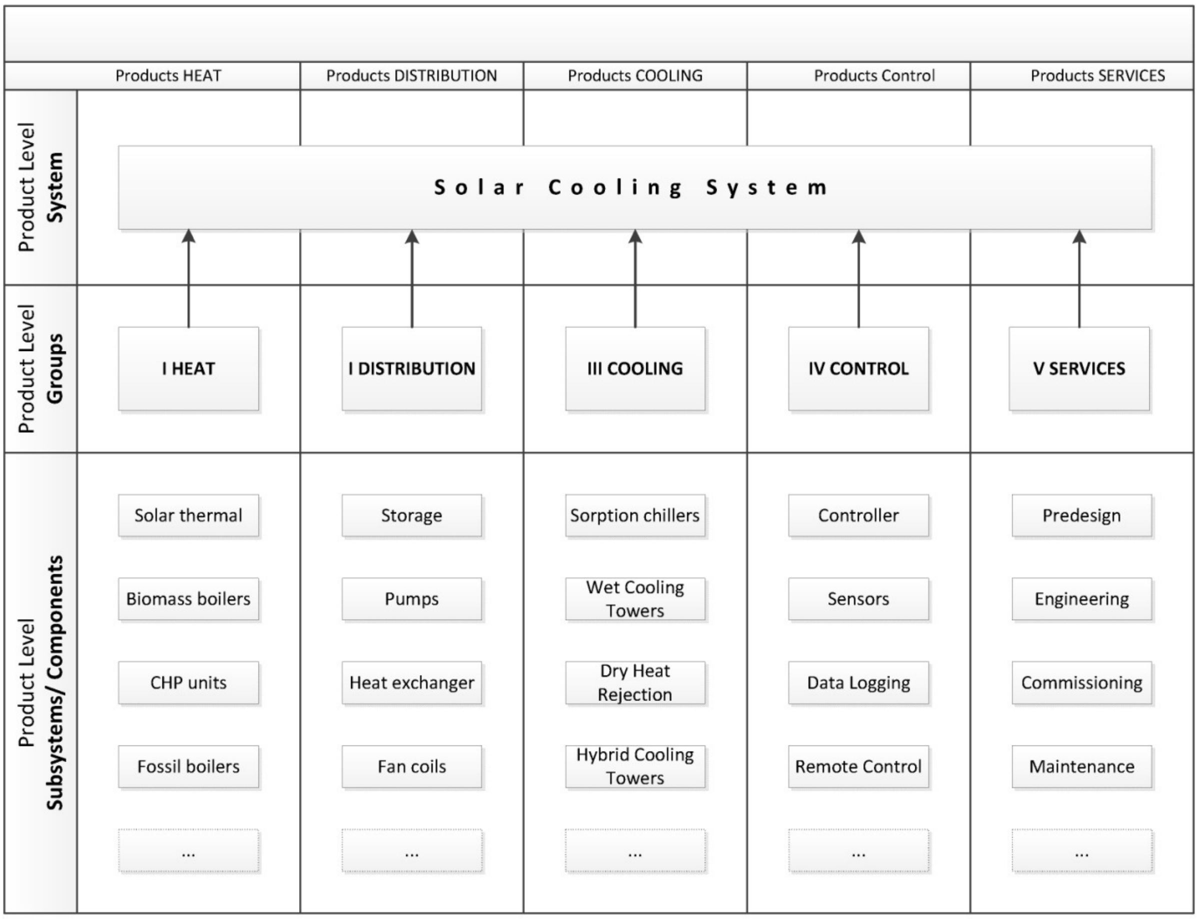


Figure 6-1: Product groups for solar cooling systems

Offering a solar cooling system to the market, means including goods and services from all the listed product groups. Focusing on these components delivers good conditions for solar cooling system design, as all elements of the product groups “Heat”, “Distribution” and “Cooling” are available to the market. However, “Control” and “Services” are missing elements for completing solar cooling system design.

While efforts for services such as pre-design, engineering and commissioning could be reduced via standardized assemblies and modules, the recommended system control can only be achieved via complex and costly efforts in customizing market available hard- and software. Recall that for entering the solar cooling market, standardized products are essential to generate competitive conditions (see section 4.5.2 Market aspects). In addition to economical issues, a standard control system leads to a higher supply guarantee, a more reliable operation and a higher system's efficiency. Pursuing the aim of creating successful solar cooling systems for the market, requires a combination of a novel control system with integrated sorption chiller systems and standardized services for specific project implementation. The following section describes the methodology of the product development process for achieving this target.

6.2 Product development

Applying the theory of nested systems ensures an integrated product development process based on systematic evaluated specifications (see Figure 6-2). With the generic design for solar cooling systems leading to a system architecture for hydraulics and control, the framework for developing integrated components such as the controller and optimized sorption systems is given. For both development fields, adequate design elements have to be identified, tested and validated before applying to implement hydraulics and control for solar cooling systems.

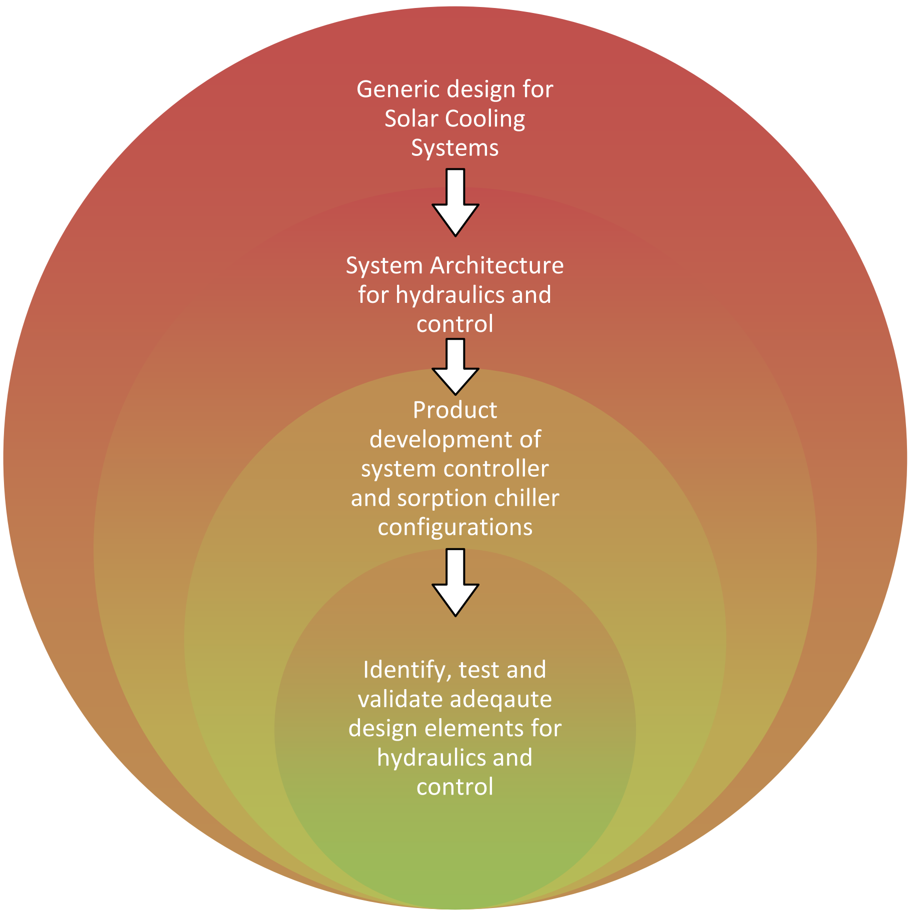


Figure 6-2: Model of Nested systems – Integrated product development

Identifying the tasks for product development ensures essential principles and methods such as target temperature control, demand oriented generation and EGM-characteristics to be considered. For coordinated and harmonized operation of a variety of applications, the overall control system represents the main portion of development effort. This product has to be developed from prototyping to series production. For the sorption systems, including several adsorption and absorption chiller types, as well as different heat rejection methods such as wet, dry or hybrid coolers, optimized hydraulic and control configurations have to be created. The identified tasks for product development lead to the necessity of having an adequate testing environment, to be able to implement the novel methods and principles via available design elements. Based on practical findings from testing, the control system as well as the configurations for sorption chiller subsystems can be developed. With standardized novel products and adequate customer services such as pre-design, engineering and commissioning, solar cooling systems for various applications can be implemented. To achieve a competitive marketing position, the product range on offer will then cover all required items to deliver customized solar cooling systems to the market. Within the following section, the product development process is illustrated, starting with describing the testing facility for hydraulics and control.

6.2.1 Testing facilities for hydraulics and controls

Figure 6-3 A and B illustrates the testing facility for product development. The author was responsible for control and system development at the SolarNext AG and therefore led the entire product development process. The strategy for development consists of an ongoing process with prototyping, testing, validation and implementation of achieved findings.

Figure 6-3 A and B: Testing facility for hydraulics and controls at SolarNext AG (Source: SolarNext AG)

The test stand for sorption chillers (see Figure 6-3 A) was created in collaboration with the author delivering hydraulic concepts and design details. With this testing facility, absorption and adsorption chillers can be operated for investigating optimized configurations. Via an integrated measurement system, the heat flow interfaces (HT, LT and MT) can be monitored to identify correlations resulting from varying temperatures and mass flows. For each sorption chiller type, the R&D team evaluated configurations for best operation conditions, because the chiller manufacturers cannot provide detailed technical information related to variable volume flows and temperatures. Using his own findings from sorption chiller operation, the configurations for different heat rejection systems were developed by the author. For control development, the author designed a testing facility enabling control strategies for various hydraulic applications to be applied (see Figure 6-3 B). With integrated actuators such as pumps, valves and mixers, hardware characteristics of the control system can be tested and validated. The interfaces of market available actuator components are evaluated concerning to their interfaces and their suitability for integrating to solar cooling systems assessed. For testing the implementation methods of control strategies such as target temperature control, sensors for temperature and fluid flow measurement are also integrated. This testing environment is essential to begin control development, as basic characteristics of hardware and software for further development are validated.

6.2.2 Development of control system

Developing a novel control system includes processing several stages for hardware and software. The author led the development team, consisting of suppliers for hard- / software and control and software engineers, giving detailed specifications and processing rules. First, a prototype based on the investigated control specifications is developed (see Figure 6-4).

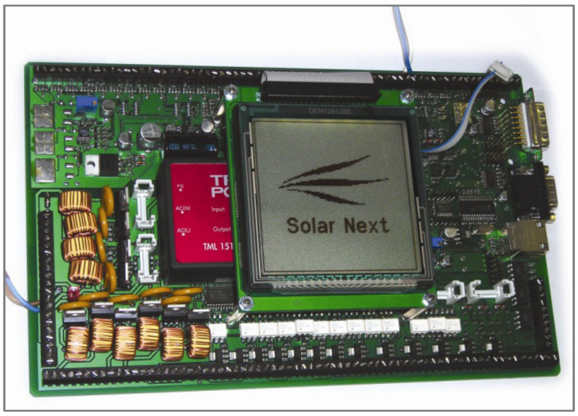


Figure 6-4: Prototype of system controller from SolarNext AG (Source: SolarNext AG)

With the testing facility (see Figure 6-3 B), operating this prototype controller delivers basic findings towards the implementation of control strategies such as target temperature control as well as characteristics for the required hardware to operate the associated actuators. The validation of novel principles and methods for control and hydraulics via the testing facility leads to realistic results for developing reliable products. For the market entry, two versions of the control system were planed (see Figure 6-5). The range of applications for pure heating purposes will be covered by the chilli® System Controller H. With up to 46,000 heating applications, this controller will be able to manage up to three different heat sources and up to four heating circuits with various characteristics. For including cooling applications, the chilli® System Controller HC will cover up to 43,000,000 different hydraulic and control applications. Hereby, the hardware of the control system is specified to have only an approximated 130 interfaces for inputs and outputs (I/O's). To cover this huge range of combinations via such a relatively low number of I/O's, requires to implement the modularity given by the generic system design.

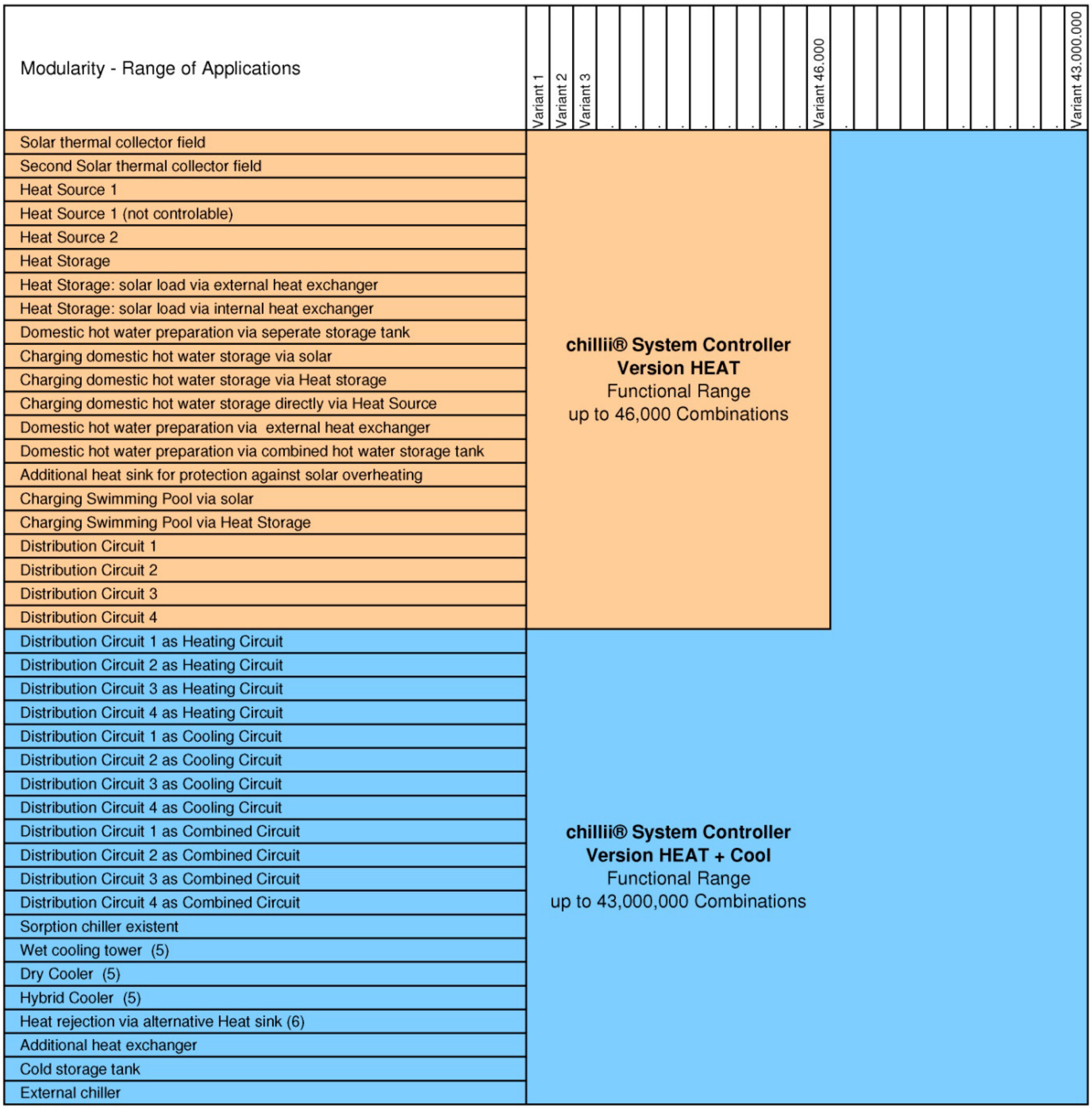


Figure 6-5: Modularity of the control system (Source: SolarNext AG)

Including this range of applications, and combining with results from prototyping, a pre-series controller with focus on market tasks such as production, implementation, operation and service was drafted (see Figure 6-7).

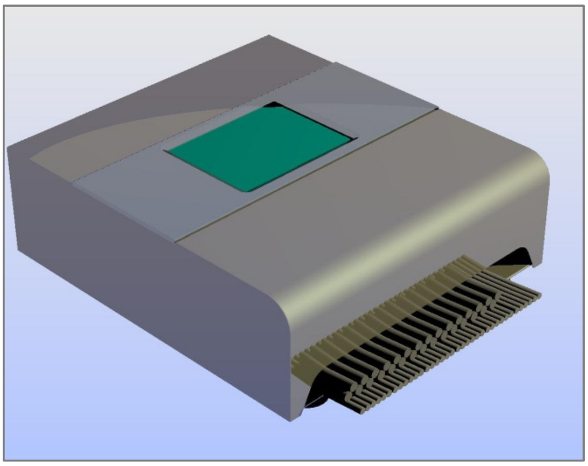


Figure 6-7: Draft of pre-series controller housing (Source: SolarNext AG)

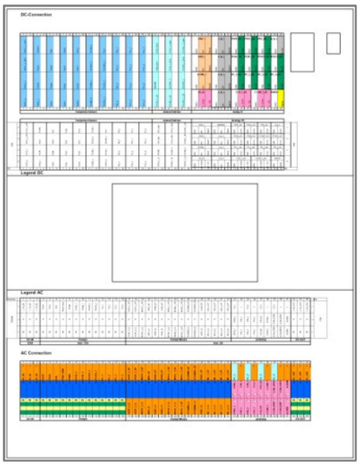


Figure 6-6: Draft of strip terminal (Source: SolarNext AG)

To integrate the high number of I/O's within a compact housing of a control system, an innovative strip terminal was created (see Figure 6-6). Via connecting sensors from the top, and connecting actuators from the bottom, the approximated 130 I/O's could be easily integrated within the controller (see Figures 6-8 and 6-9).

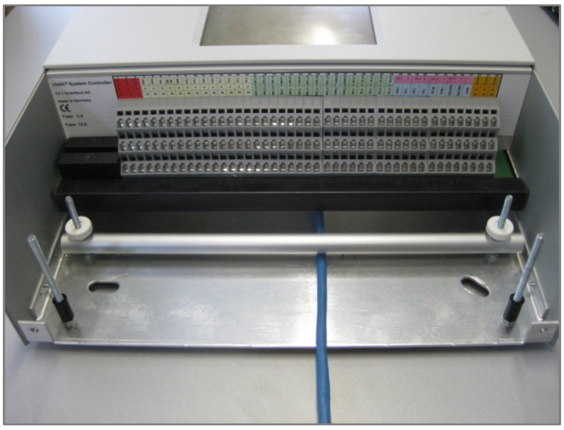


Figure 6-8: Lower strip terminal with cabel channel to upper strip terminal (Source: SolarNext AG)

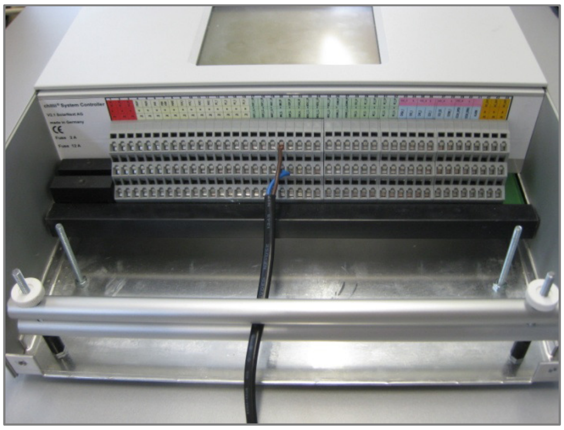


Figure 6-9: Connection to lower strip terminal (Source: SolarNext AG)

For good usability, the human interface of the control system is represented via an integrated LCD touch screen.

For adjusting settings and receiving information from operation, an intuitive graphical user interface (GUI) was developed following the author's GUI-specification (see Figures 6-10 an 6-11).

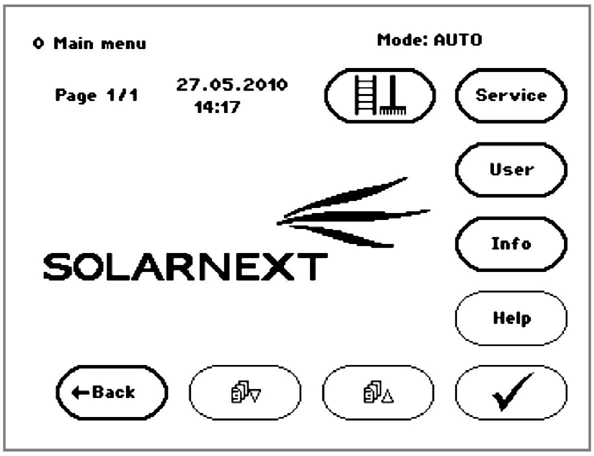


Figure 6-10: Graphical user interface (GUI) - main menu (Source: SolarNext AG)

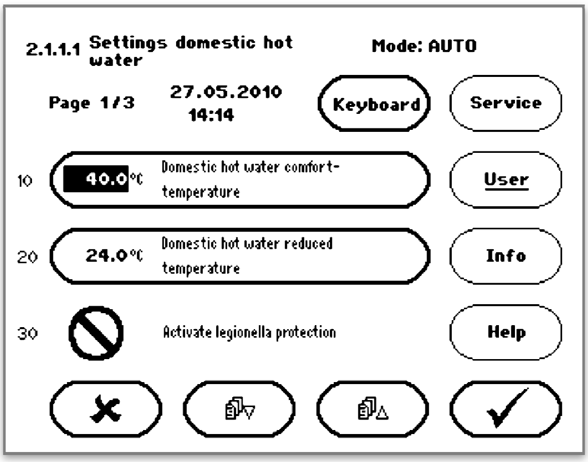


Figure 6-11: Graphical user interface (GUI) - settings menu (Source: SolarNext AG)

Via two different adjusting menus (see “Service” and “User” in Figure 6-10), settings can be changed by the operator. While the menu “Service” includes parameters for system configuration, the menu “User” offers settings for daily use such as date and time and set points for the domestic hot water preparation or the preferred room temperature. For receiving information about the present operation modes, temperatures or actuator operations, the menu “Info” provides information on all system values. Via the button “Help”, an integrated help function delivers descriptions about the present screen and gives assistance concerning common set point adjustment. Via the control buttons on the bottom of the screen, navigation between the submenus as well as adjusting set points can be achieved (see Figure 6-11). For maintenance purposes, a remote control system, enabled via an Ethernet interface, was implemented. By using the same screen design as that used in front of the controller, this function enables concise and user-friendly remote service for the customer while having a low effort. As nearly every facility supports internet access, additional installation work on site is not necessary. For service and optimization purposes, the control system is equipped with an onboard data logging device. Via an integrated SD-card slot, monitoring data can be recorded, and transferred to a desktop computer for analysis. Software updates and customized settings can also be uploaded via SD-card.

The pre-series version of the control system (see Figure 6-12) was tested and optimized via field testing facilities.

Figure 6-12: chillii® System Controller (Source: SolarNext AG)

To achieve a market-ready controller for series production, field-testing is necessary for product proofing on real applications. The ongoing procedure of testing, validation and optimization, leads to a recommended reliability of market available products. Within the following section, the field testing facility at the SolarNext AG in Rimsting , Germany is described.

6.3 Field testing facility - Improved Solar Cooling System 2010

For field testing, the pilot plant from 2007 was redesigned based on the author’s new concepts developed for control and hydraulics (see Figure 6-13 A and B).

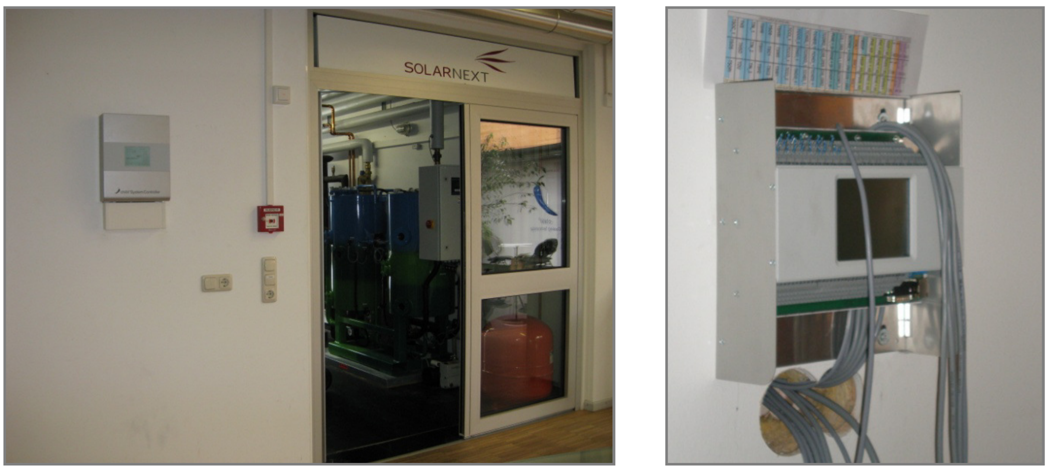


Figure 6-13 A and B: Redesign of solar cooling system within the office building in Rimsting, Germany (Source: SolarNext AG)

In addition, in early summer of 2009 a single effect water/ lithium bromide Yazaki WFC18 absorption chiller with 17.5 kW cooling capacity was installed to replace the faulty EAW Wegracal SE15 absorption chiller. A detailed comparison of both chillers is given in Table 6-1.

Table 6-1: Absorption chiller specification

Absorption chiller specification			**EAW Wegracal SE15**	**Yazaki WFC 18**
Working pair	Refrigerant		Water	Water
	Sorbent		Lithium bromide	Lithium bromide
Heat supply	Temperatures (T_{in}/T_{out})	[°C]	90/ 80	90/ 83
	Flow rate	[m³/h]	1.8	4.32
	Heat input	[kW]	21	25.1
Chilled water	Temperatures (T_{in}/T_{out})	[°C]	17/ 11	12.5/ 7.0
	Flow rate	[m³/h]	1.9	2.77
	Cooling capacity	[kW]	15	17.6
Heat rejection	Temperatures (T_{in}/T_{out})	[°C]	30/ 35	31.0/ 35.0
	Flow rate	[m³/h]	5	9.18
	Heat rejection	[kW]	35	42.7
COPth	Coefficient of performance	[-]	0.71	0.70

The cooling performance of the old and the new chillers was similar. Data from the manufacturers states that the EAW Wegracal SE15 has a thermal COP of 0.71 compared to 0.70 of the Yazaki WFC18, using generator temperatures of 88°C and 90°C respectively.

6.3.1 Description of changes to the former system

Despite a novel control system, the change to the 2007 system was in the hydraulic connectivity of the subsystems (Figure 6-14). This included modifying the solar thermal primary circuit and the charging and discharging of the thermal storage system (which includes charging by the solar system and the oil-fired boiler).

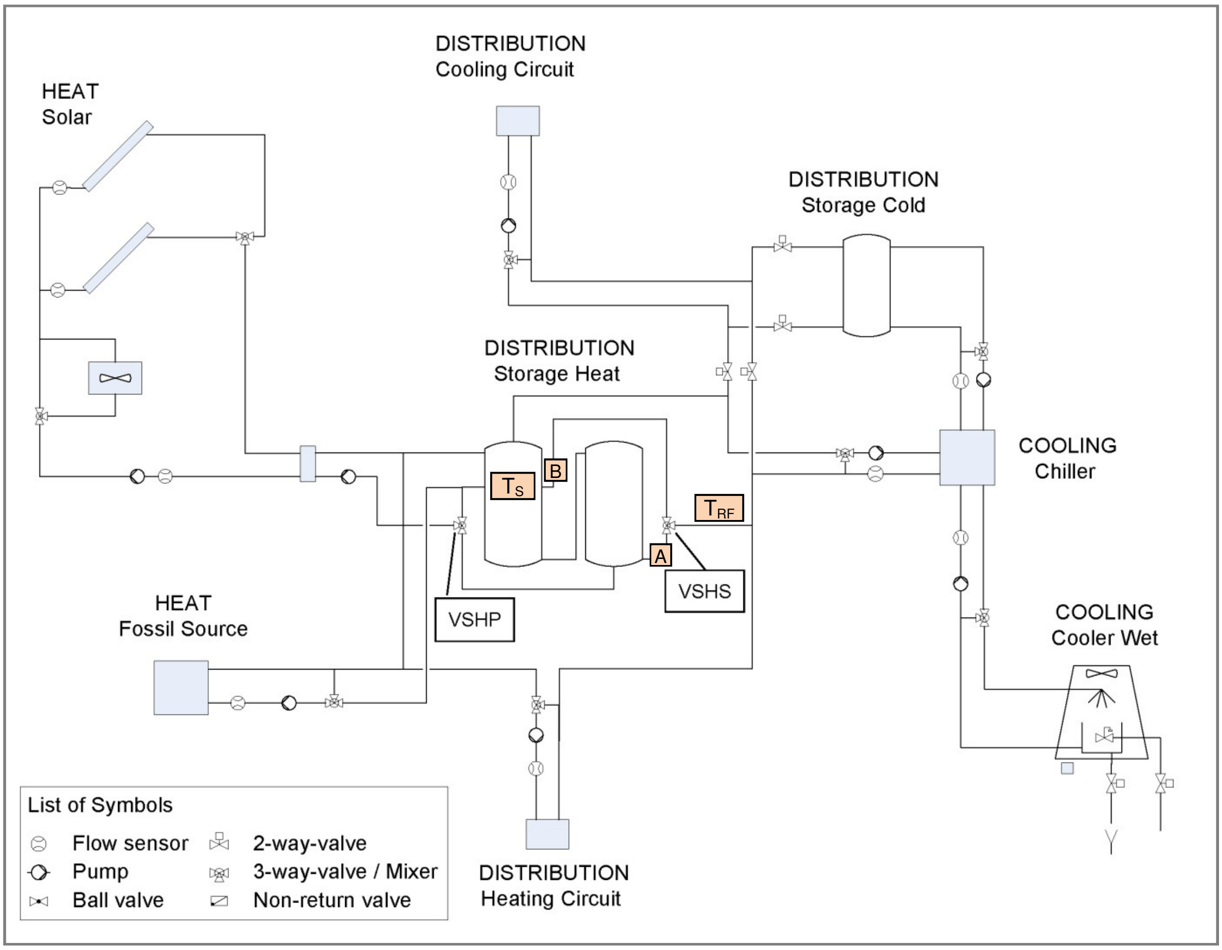


Figure 6-14: Hydraulic system of the redesigned 2010 system at the office building of SolarNext AG, Germany

The storage charging strategy of using three different spaces within the storage system was replaced by only one inlet at the top and a dynamic outlet depending on the storage temperature. These changes result from the novel control strategy via target-temperature control as well as from achieved findings from the EGM-analysis.

The same strategy is used for discharging the storage system. Compared to the 2007 system, where the heat supply flow of the absorption chiller was directed via the oil-fired boiler, the novel 2010 system supplies the chiller from the top of the heat storage system directly. The simple hydraulic structure of the generic design was implemented and organised according to the HDC-model: Heat, Distribution and Cooling. Each component is hydraulically independent. The solar thermal plant, as well as the back-up oil-fired boiler, is able to charge the hot water storage tank independently. The tanks are connected in series, and can be used for storing as well as for hydraulic separation of the components. Via two 3-way valves (see VSHP, VSHS in Figure 6-14), the storage volume used can be changed depending on the actual working point of the system. If, for example, the temperature of the upper part of the tanks is too low (see T_S in Figure 6-14), then the solar plant will only load the upper part, thus achieving the temperature required quicker and preventing the operation of the fossil system. All discharging components (heating circuits, chillers, etc.) receive their supply directly from the top of the storage system. Via the 3-way valve at the discharging side of the storage system (see VSHS in Figure 6-13), the return flow is put back to the storage tank at the appropriate level depending on its temperature T_{RF} (see Figure 6-14). As a result from entropy analysis, a simple algorithm could be applied to decide which entry point of the storage is used:

$T_{RF} < T_S$: Return flow is directed to the bottom of the storage via port A

$T_{RF} > T_S$: Return flow is directed to the top of the storage via port B

(see T_{RF}, T_S, A, B in Figure 6-14)

In summary, the entropy generation rate during charging and discharging of the storage system is minimized, leading to an improved overall efficiency of the thermal system.

6.3.2 Control Installation

One system controller replaced the four controllers installed in the 2007 plant: the chillii® System Controller. The performance and efficiency of solar cooling systems depends heavily on a sufficient heat supply for the sorption chiller. Using solar thermal energy, the focus of the control system must be to ensure a sufficient temperature to drive the sorption process. Therefore the solar control strategy of the 2010 system is based on the demand-oriented principle of target temperature control, whereas the 2007 system used the common temperature difference control strategy. The implemented philosophy of demand oriented system control firstly enables the collection of the heating and cooling demand of the distributing circuits. Secondly, it provides information of the stored energy within the storage tank. Thirdly, it leads to demand-oriented supply temperatures generated via coordinated renewable and fossil sources. The demand of cold water at 12°C for example, leads to a heating demand for supplying the sorption chiller at a temperature of 80°C, and this leads to a target temperature of 85°C within the solar collectors. By connecting and controlling every component of the entire system with one control system, surrounding conditions for the absorption chiller can be modified to achieve optimized working conditions.

6.4 Summary of implementation

This chapter has described the transfer of specifications from generic design to product development guided by the theory of nested systems. For implementing novel methods such as demand-oriented target temperature control and EGM-characteristics for hydraulics, test facilities were created. With practical findings from operating different sorption chiller configurations and different control configurations for thermal systems, design elements for product development were evaluated. The novel control system was developed from prototyping to a pre-series version for field-testing. With redesigning the existing solar cooling pilot plant from 2007, a field test facility for the novel methods and concepts for hydraulics and controls was created.

The applied methodology and the author's specifications for hydraulics and control lead to an improved solar cooling system, with a pre-series controller version that is very close to achieving market-readiness.

7. Performance metrics and validation methods

7.1 Preamble

The purpose of this chapter is to identify and develop adequate methods for validating the improvements of the 2010 system compared to the former 2007 pilot plant. With Table 7-1, an overview of the changes to the compared systems is given.

Table 7-1: Overview system changes (System 2007 and System 2010)

Subsystem/ Components	System 2007	System 2010
Heat storage system	Two 1000l standard heat storage tanks connected **in parallel**	Two 1000l standard heat storage tanks connected **in series**
Heat storage charging system	Three levels by **switching supply and return flow** (bottom, middle, top)	Two levels by switching return flow (top of first tank or both tanks) – **supply flow always to the top**
Control system/ strategy	**Four** different controllers / **temperature difference control** – control focused on subsystems	**One** system controller / **target temperature control** – control focused on entire system
Absorption chiller	EAW Wegracal SE 15	Yazaki WFC 18
Back-up heating system	Oil-fired boiler, with **return flow boost** from heat storage system	Oil-fired boiler, directly charging heat storage **for peak load only**

As the former measurement system has also been modified during redesign, both monitoring systems are considered to ensure a representatively comparable database.

7.2 Measurement systems for validation

Within the following sections, both measurement systems are described.

7.2.1 Measurement system of 2007 pilot plant

The measurement system of the pilot plant consisted of nine heat meters and one data logging device (see Figure 7-1). The heat quantity was calculated from flow rates and the temperature difference of supply and return flow. Devices for measurement were impeller flow meters and PT1000 temperature sensors.

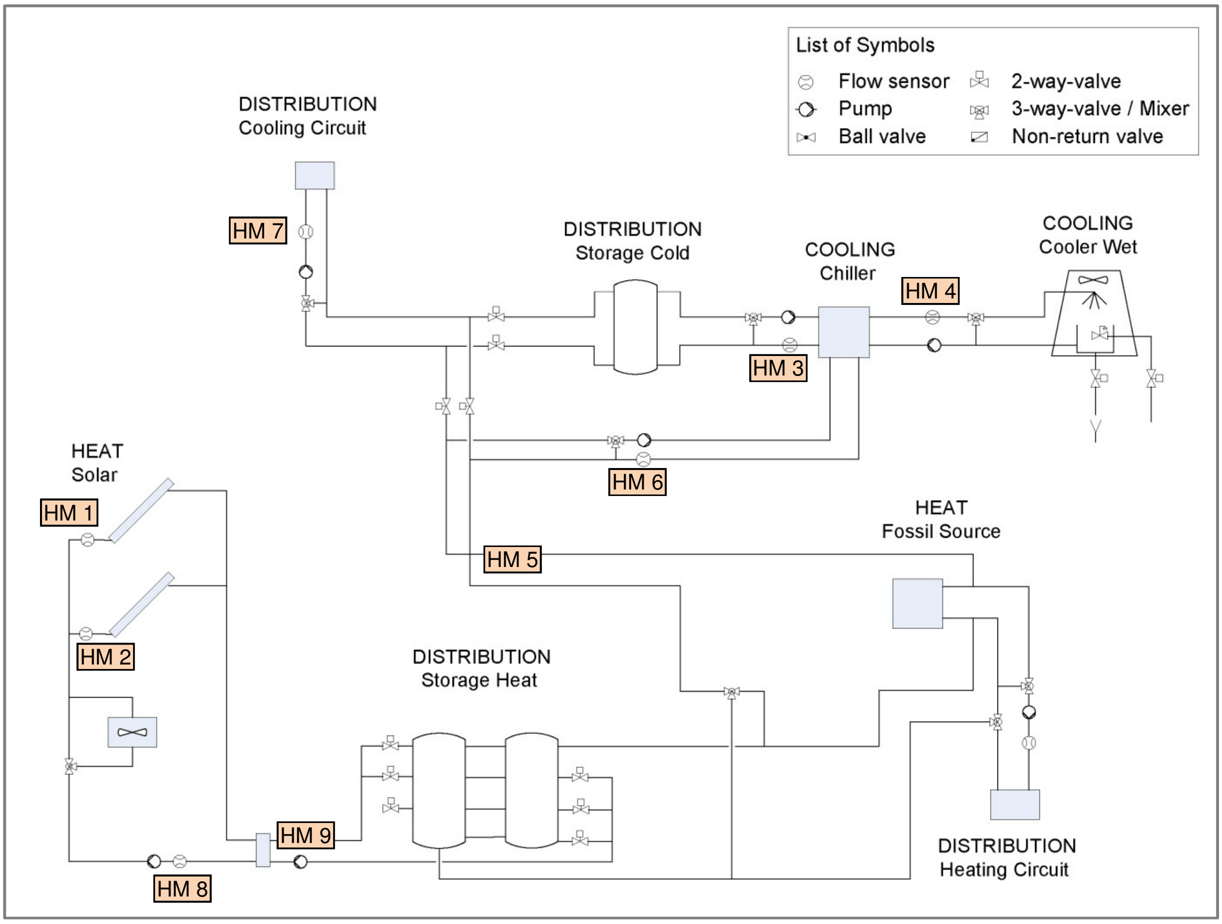


Figure 7-1: Measurement system of the 2007 pilot plant at office building SolarNext AG, Germany (Source: SolarNext AG)

Due to a step-by-step installation, not all heat meters were connected to the data logging device at the same time. The two heat meters(HM) within the primary circuit of the solar thermal system (see HM1 and HM2 in Figure 7-1) and the heat meter within the distribution circuit (HM7 in Figure 7-1), consisted of impeller flow meters and temperature sensors connected to the solar controller, which processed the measurement data and calculated the performance and energy rates. Each of the other seven heat meters consisted of one flow meter, two temperature sensors and an additional processing unit.

Some of the units were connected to the DL1 data logger from Resol, recording the monitoring data. With a low capacity of 2MB Flash storage, the measurement data had to be downloaded regularly to prevent overwriting of records by new data collected. Moreover, the data logging device sporadically shut-down, often delivering no data. The download of data had to be done via connecting the data logging device to a notebook. The measurement data was stored as a text file, which could be formatted and analyzed using MS EXCEL. Due to a complex and error-prone monitoring system, the database is not as large as it could be if recorded without a break from the beginning of operation of the pilot plant. However, the existing data is of sufficient quality for the purpose of this work.

7.2.2 Measurement system of improved 2010 system

The measurement system of the redesigned solar cooling system consists of eight heat meters (see Table 7-2), installed to determine the energy flows between the single components (see Figure 7-2).

Table 7-2: Measurement components

Measurement component	Manufacturer/ Type	Precision / Accuracy
Processing unit	Resol WMZ	0,1K / ± 0.3K
Flow meter	Resol VF 40	1 l / ± 3%
Temperature Sensors	Resol Pt1000	0,1K/ ± 0.3K
Datalogger	Resol DL 2	-

The temperature measurement was calibrated onsite after wiring using two references for each sensor (freezing and boiling point). The accuracy was proven using a mobile ultrasonic heat meter.

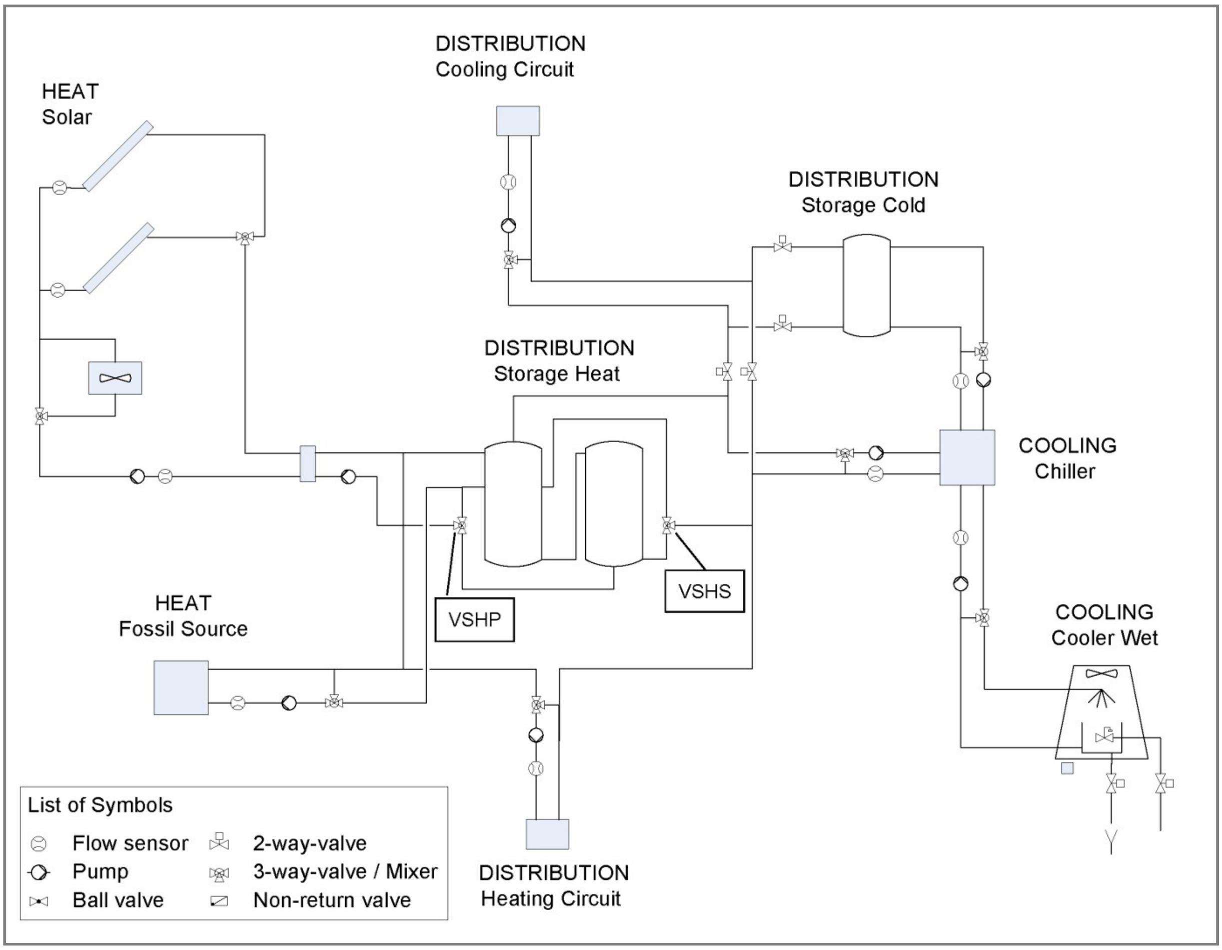


Figure 7-2: Hydraulic scheme with heat meters

All heat meters illustrated via the flow sensors in Figure 7-2, are connected to a newly installed DL2 data logging device with a higher data storage capacity and better interfaces compared to the former DL1 data logging device. Via this novel measurement system with an interface to the intranet, monitoring data could be stored since the implementation of the system in November 2009. To organise this large amount of data, a managing procedure with periodic actions for storing and processing was created. Via novel macros for MS EXCEL, stored data is summarised monthly and can easily be analyzed being illustrated in diagrams and figures.

The database enables the evaluation of different development stages as well as short-termed comparison of optimization procedures.

With the data collected from the redesigned 2010 system, and of the former 2007 system, comparable working points can be identified. For validation, adequate methods for a representative comparison of both systems are defined within the following sections.

7.3 First law efficiency factors for system comparison

Within this section, performance metrics based on the first law of thermodynamics are presented. Figure 7-3 illustrates a thermodynamic model for calculating the thermal Coefficent of Performance (COP_{th}) of sorption chillers.

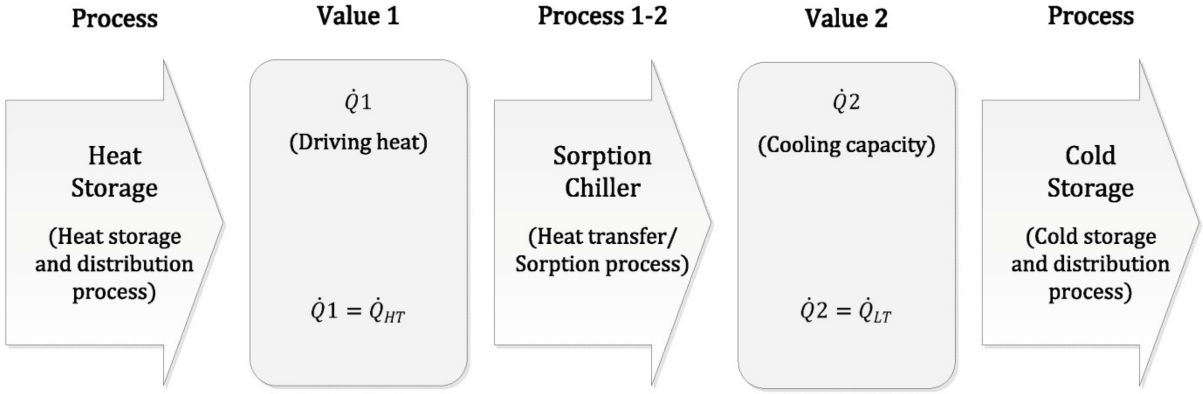


Figure 7-3: Thermodynamic model for calculating first law efficiency of sorption chillers

For driving the sorption process, the heat rate $\dot{Q}1$ (see Value 1 in Figure 7-3) is used by the machine to generate the cooling capacity $\dot{Q}2$ (see Value 2 in Figure 7-3). The ratio of cooling capacity $\dot{Q}_{LT}$ to driving heat $\dot{Q}_{HT}$ is defined as the COP_{th} of the sorption chiller [see Equation (7-1)].

$$COP_{th} = \frac{\dot{Q}2}{\dot{Q}1} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \qquad (7\text{-}1)$$

This first law efficiency factor is a common performance metric for validating absorption as well as adsorption chillers. As the sorption chiller comprises only one component of a solar cooling system, the COP_{th} delivers information about the chiller’s efficiency, but not about the overall efficiency of the system. For representative comparison of solar cooling systems, additional methods for validation are needed. Within the following section, a performance metric for validating the heat supply efficiency for driving the sorption chiller is presented.

7.3.1 Solar Supply Efficiency – SSE_{th}

Considering the methodology for evaluating the COP_{th}, the underlying thermodynamic model is extended using other components, including the previous process of storing and distributing heat to the chiller (see Figure 7-4). Analysing the heat flow of a solar cooling system, the first process is the solar thermal heat generation. The heat rate $\dot{Q}1$ (see Value 1 in Figure 7-4) is used for charging the storage and supplying the HT-interface of the sorption chiller, representing the heat storage and distribution process.

With the heat rate $\dot{Q}2$ (see Value 2 in Figure 7-4), the chiller is used to drive the sorption process. The resulting cooling capacity $\dot{Q}3$ (see Value 3 in Figure 7-4) is stored and distributed within the following cold storage and distribution process.

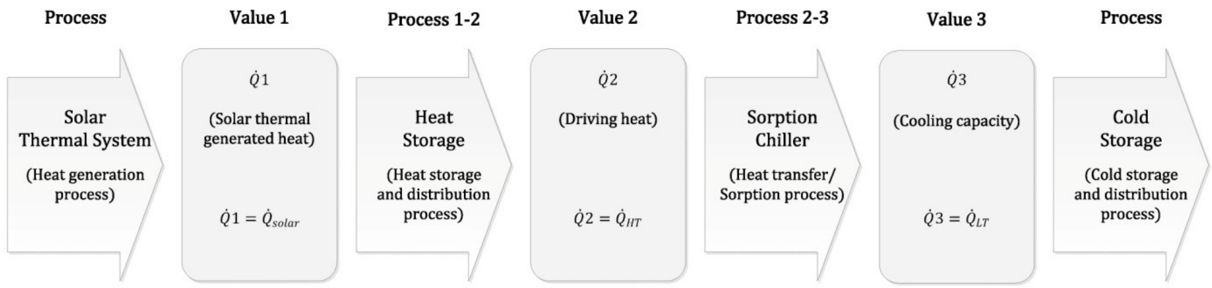


Figure 7-4: Thermodynamic model of a solar cooling system

Considering this model delivers the common COP_{th} given with Equation (7-2).

$$COP_{th} = \frac{\dot{Q}3}{\dot{Q}2} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \quad (7\text{-}2)$$

For evaluating the efficiency of the heat supply to drive the chiller, the <u>S</u>olar <u>S</u>upply <u>E</u>fficiency (SSE_{th}) of the heat storage and distribution system is used. This is defined as the ratio of driving heat $\dot{Q}_{HT}$ to the generated solar thermal heat $\dot{Q}_{solar}$ (see Equation (7-3).

$$SSE_{th} = \frac{\dot{Q}2}{\dot{Q}1} = \frac{\dot{Q}_{HT}}{\dot{Q}_{solar}} \quad (7\text{-}3)$$

Applying this novel performance metric, enables the validation of the chiller's previous heat supply process (see Figure 7-5).

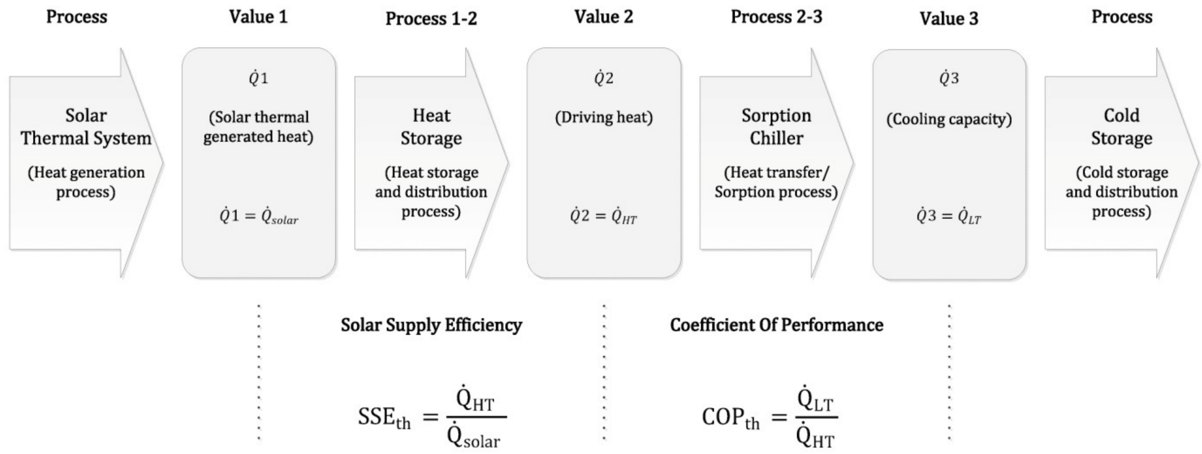


Figure 7-5: Model of a solar cooling system with the performance metrics SSE_{th} and COP_{th}

By using the novel performance metric SSE_{th}, the envelope for validation of solar cooling systems is extended relative to the existing methodology for evaluating the COP_{th}.

Methodology for evaluation of the SSE_{th}

For evaluating the SSE_{th} of solar cooling systems, only two heat meters are required. One heat meter is needed to measure the solar thermal output which is linked to the storage system, and another heat meter measures the driving heat flow to the chiller. With an additional heat meter at the LT-interface of the sorption chiller, measuring the cooling capacity, the COP_{th} can also be calculated. In summary, only three heat meters for calculating the SSE_{th}, as well as the COP_{th}, are required (see $\dot{Q}1$, $\dot{Q}2$ and $\dot{Q}3$ in Figure 7-5).

The significance of the SSE_{th}

The first law performance metric SSE_{th} states the quality of the process for storing and distributing generated heat for supplying heat consumers or in general heat demand. This efficiency factor delivers the grade of direct usable heat, as well as the efficiency of the distribution process by delivering the ratio of heat-usage-input to heat-generation-output. For validating thermal systems, this performance metric is essential when considering the heat flow between demand and generation. For thermal systems with integrated storage, the SSE_{th} also includes the efficiency of the charging and discharging process of the storage system.

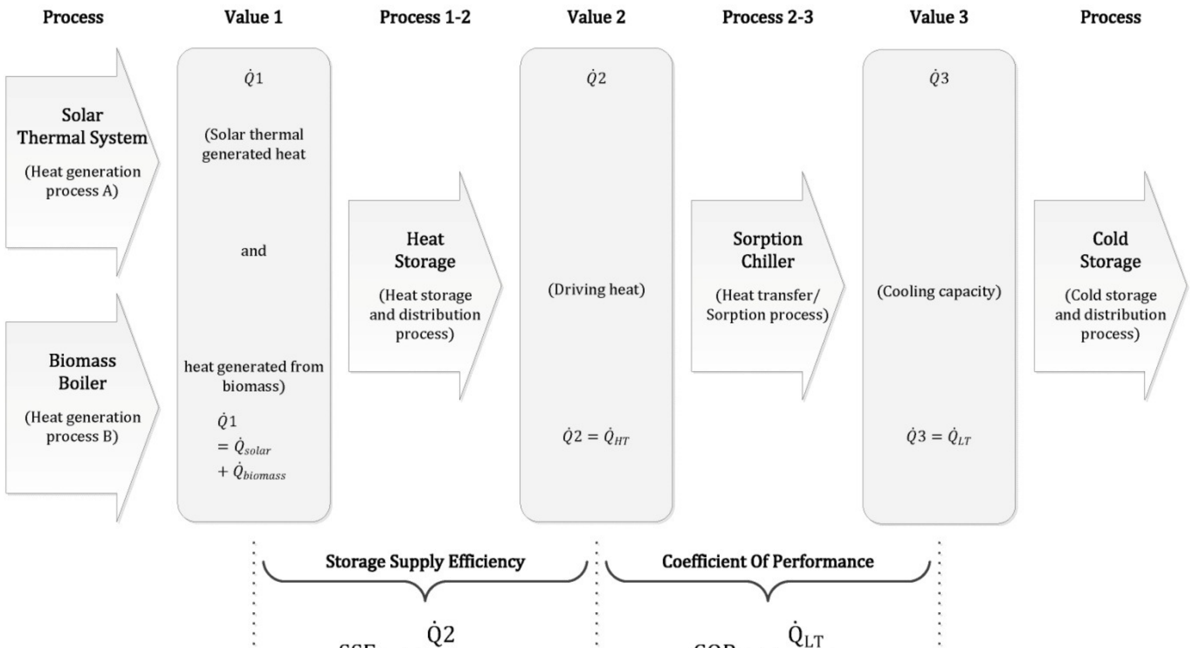
Benefits of a high SSE_{th}

A high SSE_{th} indicates a high ratio of direct usable heat from generation as well as a high efficiency of the heat linking method from generation to demand. This factor is relevant for all thermal applications including heat generation and heat consuming devices, and increases relevance with complexity of the thermal system. With an integrated storage system, a high SSE_{th} also indicates high storage efficiency, including the efficiency of the charging and discharging process.

Application to other heat sources

Considering solar cooling systems, leads to various combinations of different heat sources for heat generation. With combinations of solar thermal systems with fossil or biomass-driven boilers, applying the SSE_{th} delivers a statement towards the quality of the heat supply resulting from the specific heat source combination. When validating a heat source combination, or heat sources other than a solar thermal system, the performance metric can be named Storage Supply Efficiency leading to the same abbreviation $SSE_{th.}$

The methodology for evaluating the SSE_{th} from combinations of different heat sources is illustrated in Figure 7-6, validating a system with heat generation from a solar thermal plant and a biomass-driven boiler.



$$SSE_{th} = \frac{\dot{Q}2}{\dot{Q}1} = \frac{\dot{Q}_{HT}}{\dot{Q}_{solar} + \dot{Q}_{biomass}}$$

$$COP_{th} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}}$$

Figure 7-6: Model of a solar cooling system with different heat sources

Equation (7-4) shows the general proceeding for calculating the SSE_{th} for systems with more than one heat source.

$$SSE_{th} = \frac{\dot{Q}2}{\dot{Q}1} = \frac{\dot{Q}_{HT}}{\sum \dot{Q}_{heat\ sources}} \qquad (7\text{-}4)$$

The usable heat rate is then divided by the sum of heat generated by all the heat sources involved.

For applications with several heat sources and different heat sinks, as shown in Figure 7-7, the methodology for evaluation is extended by also adding the heat rates of all the consumers.

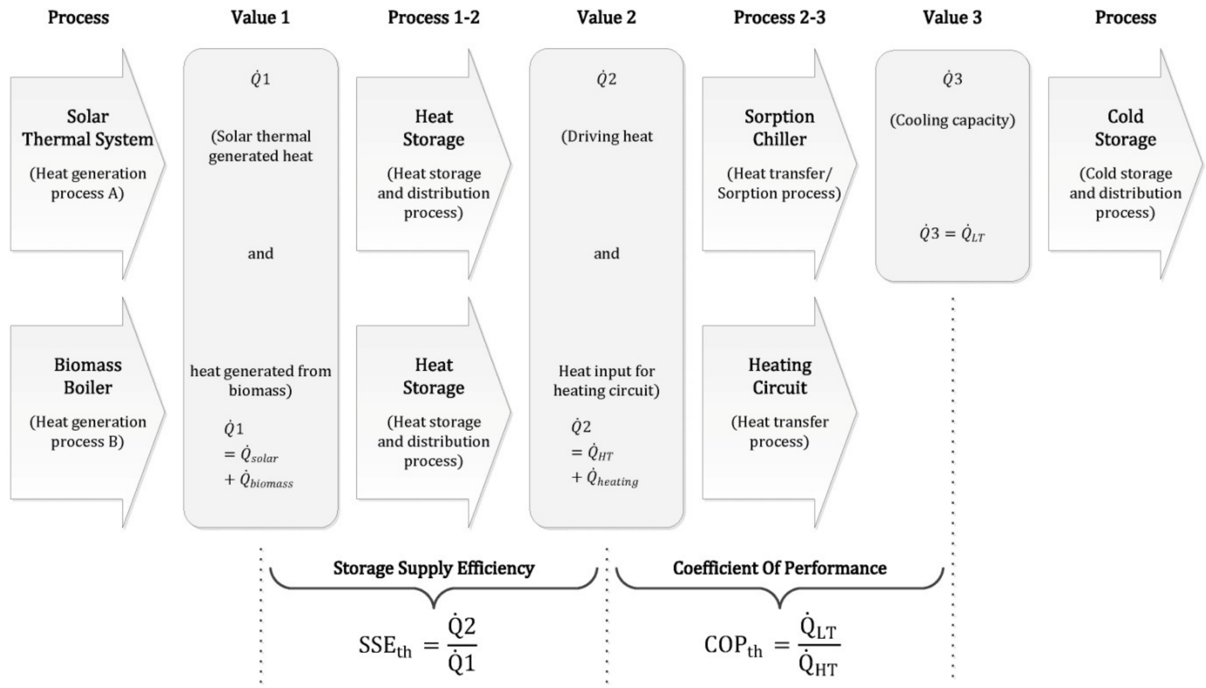


Figure 7-7: Model of a solar cooling system with different heat sources and heat sinks

Calculating the SSE_{th} for systems with more than one heat source and more than one heat consumer yields Equation (7-5).

$$SSE_{th} = \frac{\dot{Q}2}{\dot{Q}1} = \frac{\sum \dot{Q}_{heat\ sinks}}{\sum \dot{Q}_{heat\ sources}} \qquad (7\text{-}5)$$

The sum of heat distributed to all heat consumers is then divided by the sum of the heat generated by all heat sources. The calculation of the COP_{th} is not affected. For evaluating the SSE_{th} of systems with several heat sources and heat consumers, each heat flow has to be measured, leading to one heat meter per generating unit and one heat meter per consuming device.

7.3.2 Solar Cooling Efficiency – SCE_{th}

Considering validation methods for solar cooling systems, leads to a combination of the existing performance metric COP_{th} with the novel efficiency factor SSE_{th}. As both factors describe direct connected parts of a thermodynamic process, the multiplication of the SSE_{th} with the COP_{th} delivers a novel performance metric describing the combined efficiency of both processes. Equation (7-9) shows the definition of the Solar Cooling Efficiency (SCE_{th}).

$$SCE_{th} = SSE_{th} \cdot COP_{th} \quad (7\text{-}6)$$

Inserting Equations (7-2) and (7-3) into (7-6) yields Equation (7-7), describing the SCE_{th} via the ratio of cooling capacity to solar thermal output.

$$SCE_{th} = \frac{\dot{Q}_{LT}}{\dot{Q}_{solar}} \quad (7\text{-}7)$$

Considering the thermodynamic model of a solar cooling system illustrates the correlations between existing and novel performance metrics (see Figure 7-8).

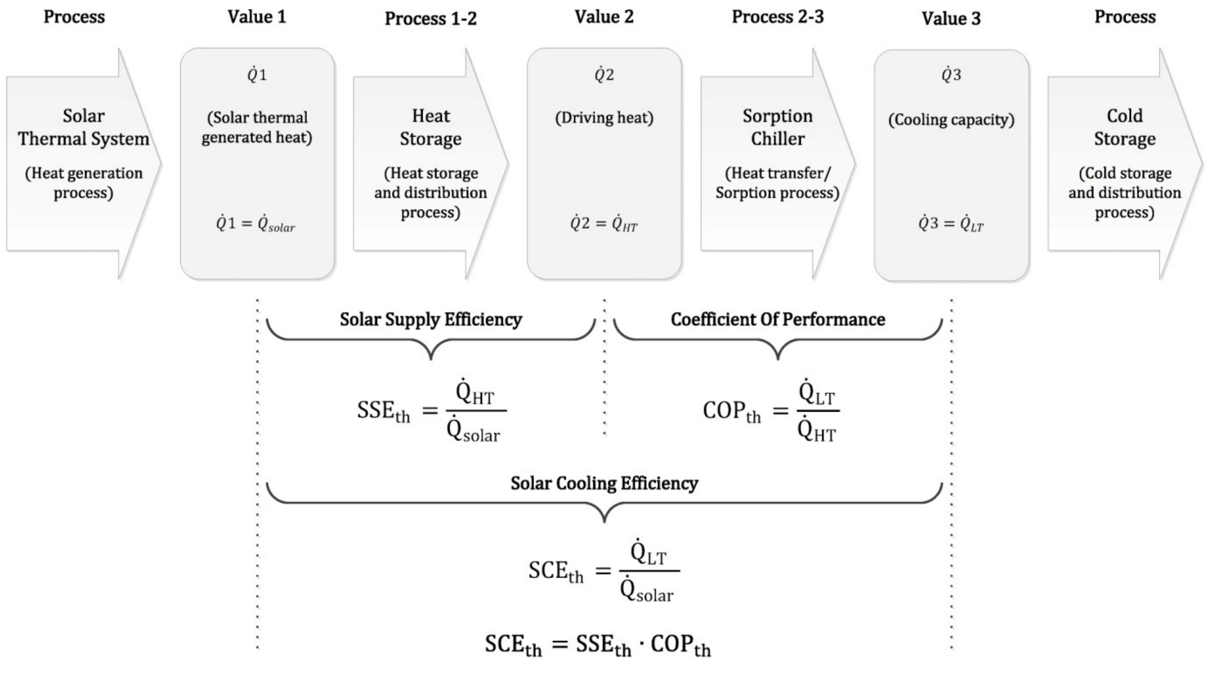


Figure 7-8: Model of a solar cooling system showing the performance metrics SSE_{th} , COP_{th} and SCE_{th}

The SCE_{th} describes the quality of the cold generation process from heat generation output to cold distribution input, representing a system's efficiency. In addition to the benefits of the novel factor $SSE_{th,}$ the combination with the established COP_{th} provides an easy and concise rating method for benchmarking solar cooling systems. Considering other heat sources for driving the sorption chiller, the performance metric can be named Supply Cooling Efficiency leading to the same abbreviation SCE_{th}. Despite of the definitions and examples for evaluating the SSE_{th}, the evaluation of the SCE_{th} is based on a direct accountability of the heat generated to the amount of heat for driving the sorption process. This task has to be clarified for systems with more than one heat consuming unit to ensure a representative performance metric (compare Figure 7-7 and Figure 7-8).

7.4 Performance metrics for comparison of sorption and compression chillers

As compression and sorption chillers are interchangeable products for covering the same demand, those units are often compared using their performance characteristics. One way is the comparison of capital costs considering the life cycles of each technology. Another way is to validate the thermodynamic performance. For sorption chillers, two metrics for expressing the efficiency of this chiller type are available – firstly the thermal COP_{th} [see Equation (7-8)] and secondly the electrical COP_{el} [see Equation (7-9)], where the thermal COP_{th} represents the wide spread performance metric for sorption chiller validation.

$$COP_{th\,sorp} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \tag{7-8}$$

$$COP_{el\,sorp} = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} \tag{7-9}$$

For validating compression chillers, the electrical $COP_{el\,comp}$, shown in Equation (7-10), represents the common performance metric for comparison. A thermal equivalent is not available, because of pure electric driving energy [see Equation (7-11)].

$$COP_{el\,comp} = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} \tag{7-10}$$

$$COP_{th\,comp} = \frac{\dot{Q}_{LT}}{?} \tag{7-11}$$

However, a representative direct comparison of compression with sorption chillers, applying the COP's mentioned above, resulting from different driving energy forms such as electrical work for the compression and heat for the sorption units is not available.

Previous investigations in performance metrics for the comparison of sorption with compression chillers avoided solving this task by applying another validation perspective such as focusing on primary energy, capital costs or on the amount of renewable driving energy including metrics such as the solar fraction. Some of the approaches are useful, but none closes the gap for direct comparison of sorption with compression chillers. When focusing on capital costs for validating interchangeable technologies only the actual market status is considered leading to an advantage for the established technology and neglecting sustainable issues such as environmental needs. Focusing on primary energy delivers a more representative result for comparing sorption with compression chillers, but fails when driving power is renewably generated for both technologies.

Furthermore, the exergy destruction caused by driving the machines with different energy forms has not been considered when comparing sorption with compression chillers.

7.4.1 Coefficient Of Performance including energy conversion - COP_{con}

The approach for identifying performance metrics for a representative comparison of compression with sorption chillers is based on the abductive guess of having to validate the exergy destruction caused by the irreversible energy conversion rates of each technology.

Hypothesis and derivation for validating energy conversion:

To validate machines or processes for thermal applications, all performance metrics must be related to the thermal energy level as this represents the benefit of the process. A representative validation of efficiency and performance must include the quality of the energy form. The quality or value of a specific energy form is known as its exergy content. Heat with a low temperature (< 100°C) is known to have a very low exergy, as this metric is defined to describe the ability for technical work.

That means that energy forms such as electrical work, kinematic and potential energy used to drive the process, must be transferred to a thermal equivalent for including the exergy destruction caused by the irreversible energy conversion. With thermal applications at temperatures around the environmental temperature level, the exergy perspective is not meaningful for validating thermal machines. On the other hand, the conversion of an energy form with a high exergy content such as electricity must be rated when used for a low-exergy-level application.

This perspective leads to the assumption that with all energy forms, except for heat, used for generating a “low-temperature” heat supply, the energy’s ability for work is lost, leading to be rated such as irreversible heat.

General principle of performance metrics:

To achieve a representative performance metric, the ratio of benefit to effort should be included as well as the amount of irreversible power resulting from energy conversion to enable the operation of the machine. For a representative comparison of different technologies, the efficiency factors must be calculated based on the same fundamentals and rules.

Equation (7-12) shows the general principle of calculating the COP of machines.

$$COP = \frac{benefit}{effort} \tag{7-12}$$

For sorption chillers, the performance metric representing the essential operation principle is described via the thermal COP_{th} defined in Equation (7-13).

$$COP_{th\,sorp} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \quad (7\text{-}13)$$

For compression chillers, the representative performance metric is described via the electrical COP_{el} (see Equation (7-14)).

$$COP_{el\,comp} = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} \quad (7\text{-}14)$$

The amount of irreversible power resulting from energy conversion $\dot{E}_{irr\,con}$ is defined as follows:

$\dot{E}_{irr\,con}$ *includes the amount of power to drive the device being converted with exergy destruction to achieve the benefit energy form of the process.*

To include the validation of the driving energy conversion rate for each technology, the conversion factor f_{con} is defined as the ratio of driving power to irreversible power [see Equations (7-15) and (7-16)]. Considering sorption and compression chillers, the irreversible efforts for energy conversion result from electric power $\dot{W}_{el}$. Auxiliary devices such as pumps, controls and fans are included via $\dot{W}_{el\,aux}$.

$$f_{con\,sorp} = \frac{driving\ power}{irreversible\ power} = \frac{\dot{Q}_{HT} + \dot{W}_{el\,aux}}{\dot{E}_{irr\,con}} = \frac{\dot{Q}_{HT} + \dot{W}_{el\,aux}}{\dot{W}_{el\,aux}} > 1 \quad (7\text{-}15)$$

$$f_{con\,comp} = \frac{driving\ power}{irreversible\ power} = \frac{\dot{W}_{el} + \dot{W}_{el\,aux}}{\dot{E}_{irr\,con}} = \frac{\dot{W}_{el} + \dot{W}_{el\,aux}}{\dot{W}_{el} + \dot{W}_{el\,aux}} = 1 \quad (7\text{-}16)$$

A high f_{con} implies a low ratio of transformed energy, and therefore describes a low entropy generation rate, as well as a low exergy destruction rate. For compression chillers, the ratio f_{con} yields 1, resulting from a 100% conversion rate for driving the unit. Combining the established COPs with the specific conversion factors [see Equations (7-15) and (7-16)], yields Equations (7-17) and (7-18) for the novel performance metric COP_{con}.

$$COP_{con\,el\,sorp} = COP_{th\,sorp} \cdot f_{con\,sorp} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \cdot \frac{\dot{Q}_{HT} + \dot{W}_{el\,aux}}{\dot{W}_{el\,aux}} > COP_{th} \qquad (7\text{-}17)$$

$$COP_{con\,el\,comp} = COP_{el\,comp} \cdot f_{con\,comp} = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} \cdot 1 = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} = COP_{el} \qquad (7\text{-}18)$$

$COP_{con\ el\ comp}$ is equal to the established COP_{el} for benchmarking compression chillers [see Equation (7-10)]. This fact enables a direct comparison of sorption with compression chillers, as the $COP_{con\ el\ sorp}$ delivers an equivalent performance metric to the electrical COP_{el} of compression chillers. The conversion factor $f_{con\,sorp}$ has to be evaluated for each specific sorption chiller subsystem to achieve comparable results. With a given conversion factor of a sorption chiller and an electrical COP_{el} of a compression chiller, the thermal equivalent $COP_{con\ th\ comp}$ for comparison with the thermal COP_{th} of the sorption chiller can also be calculated [see Equation (7-19)].

$$COP_{con\,th\,comp} = \frac{COP_{el\,comp}}{f_{con\,sorp}} \qquad (7\text{-}19)$$

Examples for proceeding:

For compression chillers f_{con} =1, resulting from driving with pure electrical energy.

With all energy efforts for auxiliary devices included within the driving power $\dot{W}_{el}$ yields Equation (7-20) for the COP_{el}.of an Airwell IAL20 compression chiller supplying cold water at 7°C at an ambient temperature of 25°C (Airwell Deutschland GmbH 2011).

$$COP_{el} = COP_{con\,el\,comp} = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} = \frac{21.3kW}{4.6kW} = \mathbf{4.63} \qquad (7\text{-}20)$$

For sorption chillers, f_{con} takes a specific value depending on the sorption chiller type and the auxiliary components such as heat supply, cold distribution and heat rejection (see Figure 7-9).

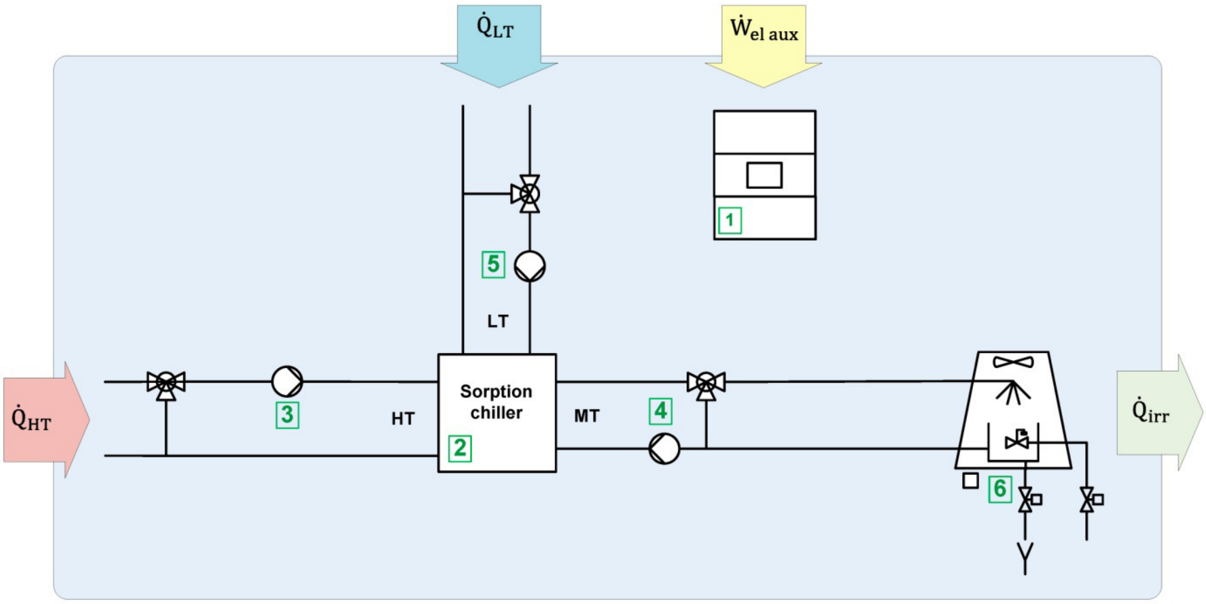


Figure 7-9: Absorption chiller subsystem for validation

As an example, f_{con} is calculated for a sorption chiller subsystem with equal operation conditions (cold water supply: 7°C, ambient temperature: 25°C), consisting of a Yazaki WFC18 absorption chiller (Yazaki Europe Limited 2008), pumps for supplying all hydraulic interfaces and a wet cooling tower with integrated fan (SolarNext AG 2010):

$$f_{con\ sysWFC18} = \frac{\dot{Q}_{HT} + \dot{W}_{el\ aux}}{\dot{W}_{el\ aux}} = \frac{25.1kW + 1.71kW}{1.71kW} = 15.61 \qquad (7\text{-}21)$$

Equation (7-21) substituted into Equation (7-17) yields Equation (7-22) for the representative $COP_{con\ el\ sysWFC18}$.

$$COP_{con\ el\ sysWFC18} = COP_{th\ WFC18} \cdot f_{con\ sysWFC18} = 0.70 \cdot 15.61 = \mathbf{10.93} \qquad (7\text{-}22)$$

Combining the established COPs with f_{con} delivers representative electrical and thermal performance metrics $COP_{con\ el\ sorp}$ and $COP_{con\ th\ comp}$ for direct comparison of sorption chillers with compression chillers, resulting from integrating irreversible energy conversion. This method is suitable to apply to all low-temperature heat-supply machines for direct comparison of different types or technologies.

7.5 Summary of validation methods

This chapter has described established and novel performance metrics for validating improvements in thermal system design. By analysing the measurement systems of the 2007 pilot plant and the 2010 solar cooling system, an appropriate database for validation is ensured. With the novel performance metric SSE_{th}, the limits of the system for validating solar cooling systems is extended by considering the existing methodology for evaluating the COP_{th}. The SSE_{th} enables an easy and clearly defined rating for all thermal systems, benchmarking the heat flow linking between generation and demand, whether for pure heating or for heating and cooling applications. Combining the established COP_{th} with the novel SSE_{th} gives the novel performance metric SCE_{th}, describing the quality of the cold generation process from heat generation output to cold distribution input. This novel system's efficiency enables an easy and clearly defined benchmarking of solar cooling systems, as the effort for evaluation is very low, requiring only three heat meters. With the definition of the conversion factor f_{con}, a validation method for direct comparison of sorption and compression chillers is developed. By validating the application of electrical work for a thermal benefit, irreversible conversion efforts are included, leading to the representative performance metric COP_{con} for the comparison of different technologies. Applying this method for the comparison of solar thermally driven sorption systems with compression chiller technology yields a 2-3 times higher efficiency of solar cooling systems with sorption technology. This method can be applied to all heat-supply machines which require a certain amount of electricity for driving the operation of the device. Furthermore, this method firstly includes the evaluation of applying different energy forms for a certain energy benefit.

8. Validation of the novel design

8.1 Preamble

Within this chapter, the validation of the novel design is presented. It is done via comparing performance metrics of the 2007 system with the redesigned 2010 system. With Table 8-1, an overview of the compared systems is given.

Table 8-1: Overview System 2007 and System 2010

Subsystem/ Components	System 2007	System 2010
Solar thermal system	37 m² flat plate collectors 36 m² vacuum tubes, orientation 180° (south), declination 45°	37 m² flat plate collectors 36 m² vacuum tubes, orientation 180° (south), declination 45°
Heat storage system	Two 1000l standard heat storage tanks connected in parallel	Two 1000l standard heat storage tanks connected in series
Heat storage charging system	Three levels by switching supply and return flow (bottom, middle, top)	Two levels by switching return flow (top of first tank or both tanks) – supply flow always to the top
Control system/ strategy	Four different controllers / temperature difference control – control focused on subsystems	One system controller / target temperature control – control focused on entire system
Absorption chiller	EAW Wegracal SE 15	Yazaki WFC 18
Cold storage system	One 1000l standard cold storage tank	One 1000l standard cold storage tank
Heat rejection system	Axima EWK 036, wet cooling tower	Axima EWK 036, wet cooling tower
Cold distribution	Fan coils/ chilled ceiling panels	Fan coils/ chilled ceiling panels
Back-up heating system	Oil-fired boiler, with return flow boost from heat storage system	Oil-fired boiler, directly charging heat storage for peak load only

Having databases of both solar cooling systems, comparable working points have to be identified for a representative validation of improvements. To highlight the differences between the systems due to their characteristics in operation, temperature / performance curves and energy sums are considered for both systems. For ensuring comparable climate conditions for validation, the periods selected for comparison were a day in July 2008 and a day in July 2010. Furthermore, both systems operate in a pure solar thermally driven cooling mode during the whole day. This fact enables a representative validation of daily energy sums as well. Firstly, operation characteristics of the solar thermal heat generation and the absorption chillers of both systems are analysed via temperature and performance curves.

8.2 Comparison of temperature and performance curves

Analysing the solar thermal heat generation, measurement values such as the collector temperature, the solar supply flow temperature charging the storage system, the global irradiation and the solar thermal performance are illustrated. In Figure 8-1, the result of the solar temperature difference control of the 2007 system is shown.

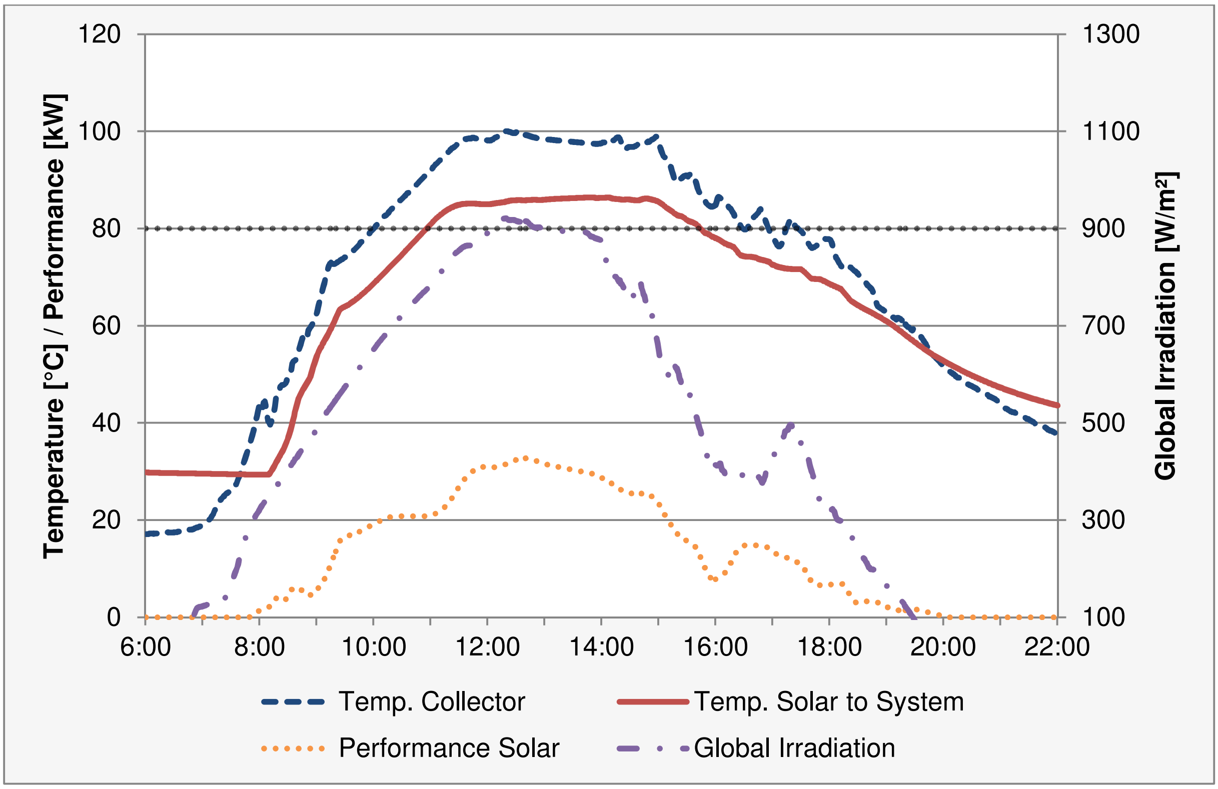


Figure 8-1: System 2007 – solar thermal plant with temperature difference control (measurement data of July 2008)

For efficient operation of the sorption chiller used, a temperature of 75°C should be supplied. Therefore, allowing for system losses, a set point of 80°C in the solar system should achieve this. The 2007 system achieves such a temperature (see red marked data curve in Figure 8-1) for approximately 4.5 hours (from 11:00 – 15:30).

In Figure 8-2, the 2010 system, with demand oriented control, supplies the store with the required temperature of 80°C (see red marked data curve in Figure 8-2)for approximately 8 hours (from 09:00 to 17:00). In contradiction to the 2007 system with temperature difference control, the 2010 system using target temperature control is focused on generating heat at a direct usable temperature. As shown in Figure 8-2, until solar irradiation is sufficient, the supply flow temperature of the solar thermal system is controlled around the setpoint of 80°C. This is done by adjusting the mass flows via the primary and secondary speed controlled solar pumps.

With target temperature control (Riechert, Obert 1991), solar thermal energy can be used immediately by the chiller. This enables the system to eliminate fossil heat sources as early as possible.

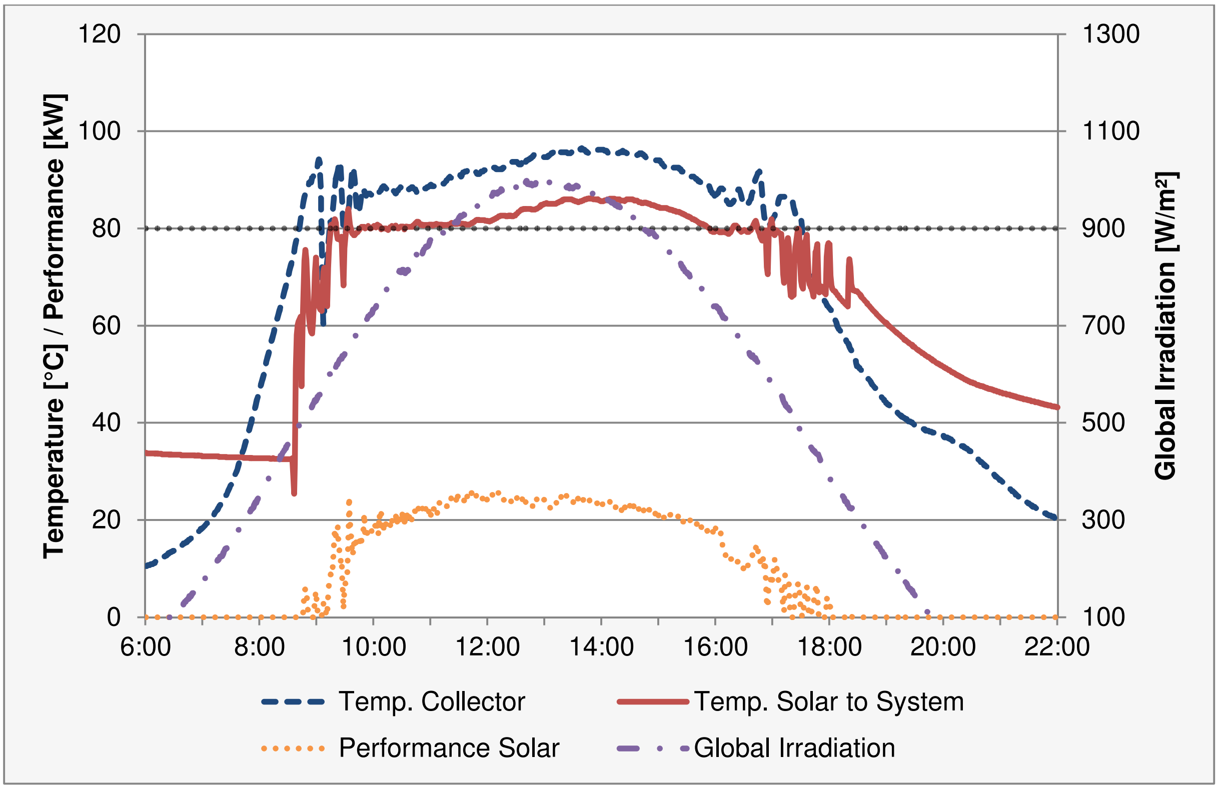


Figure 8-2: System 2010 - solar thermal plant with system temperature control (July 2010)

The solar thermal performance curves of system 2007 and system 2010 (see orange marked data curves in Figure 8-1 and Figure 8-2) illustrate a deviation in maximum power output even though the solar thermal systems had not been changed.

Investigating the solar thermal system showed that the significant lower solar thermal performance of the 2010 system was caused by the reduced efficiency of the vacuum tubes. During the approximately three years of operation, most of the vacuum insulation was lost, leading to higher thermal losses.

Analysing the absorption chiller operation of both systems, measurement values of the HT and LT interfaces of the machines are illustrated, consisting of supply and return flow temperatures (temperatures HT/LT IN/OUT) and heat flow rates (performance HT/ LT). In Figure 8-3 and Figure 8-4 the impact on the chiller performance of the different solar control strategies are shown. In Figure 8-3, the required temperature of 75°C for an efficient operation of the chiller was achieved for approximately 2 hours. The slow rising supply temperature caused a delayed start of the cooling system. A cooling performance of 10kW (nominal cooling capacity: 15kW, see Table 6-1) was first reached with the 2007 system at 12:00. The chiller performance reduces, as the heat supply temperature falls, until shut-down at 18:30.

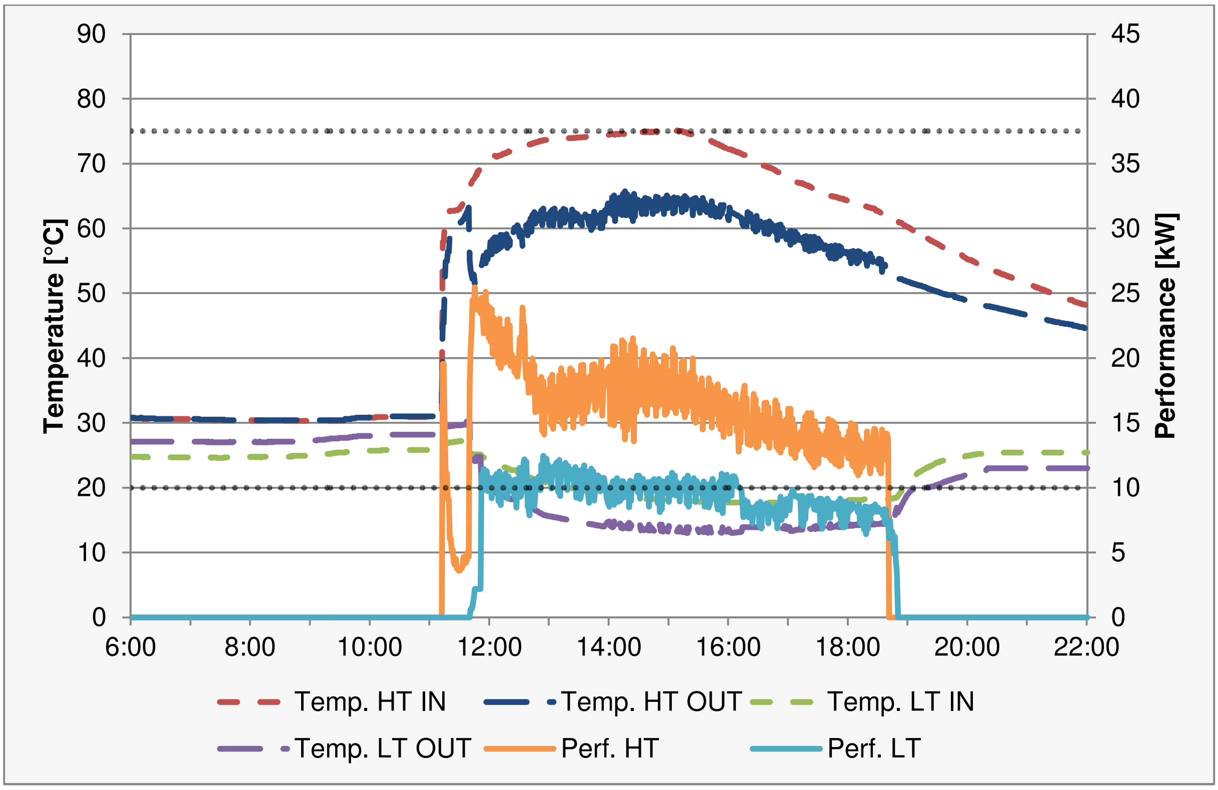


Figure 8-3: System 2007 - Operation of sorption chiller (July 2008)

Using the 2010 system (Figure 8-4), the required temperature of 75°C was achieved from 09:30 to 17:00 (7.5 hours). The significantly higher amount of heat at a direct usable temperature is a result of target temperature control applied by the 2010 system.

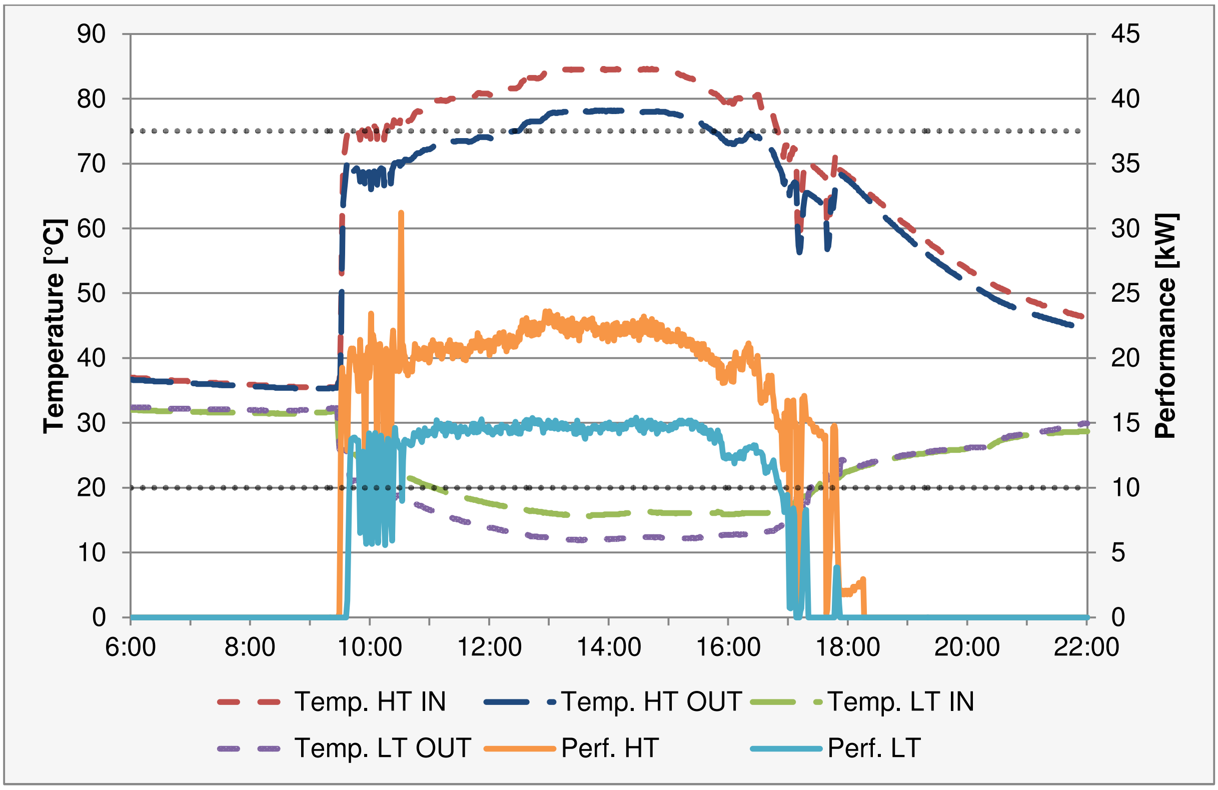


Figure 8-4: System 2010 - Operation of sorption chiller with system control (July 2010)

A cooling performance of 15kW was reached during operation between 09:30 and shut-down at 17:30 (nominal cooling capacity: 17.6kW, see Table 6-1).

With enough solar irradiation, the solar thermal plant in the 2010 system provides a sufficient temperature from the beginning of heat generation (Figure 8-2). As shown in Figure 8-5 the redesigned 2010 system provides a solar heat supply at a temperature of over 80°C for 8 hours (3.5 hours more than system 2007).

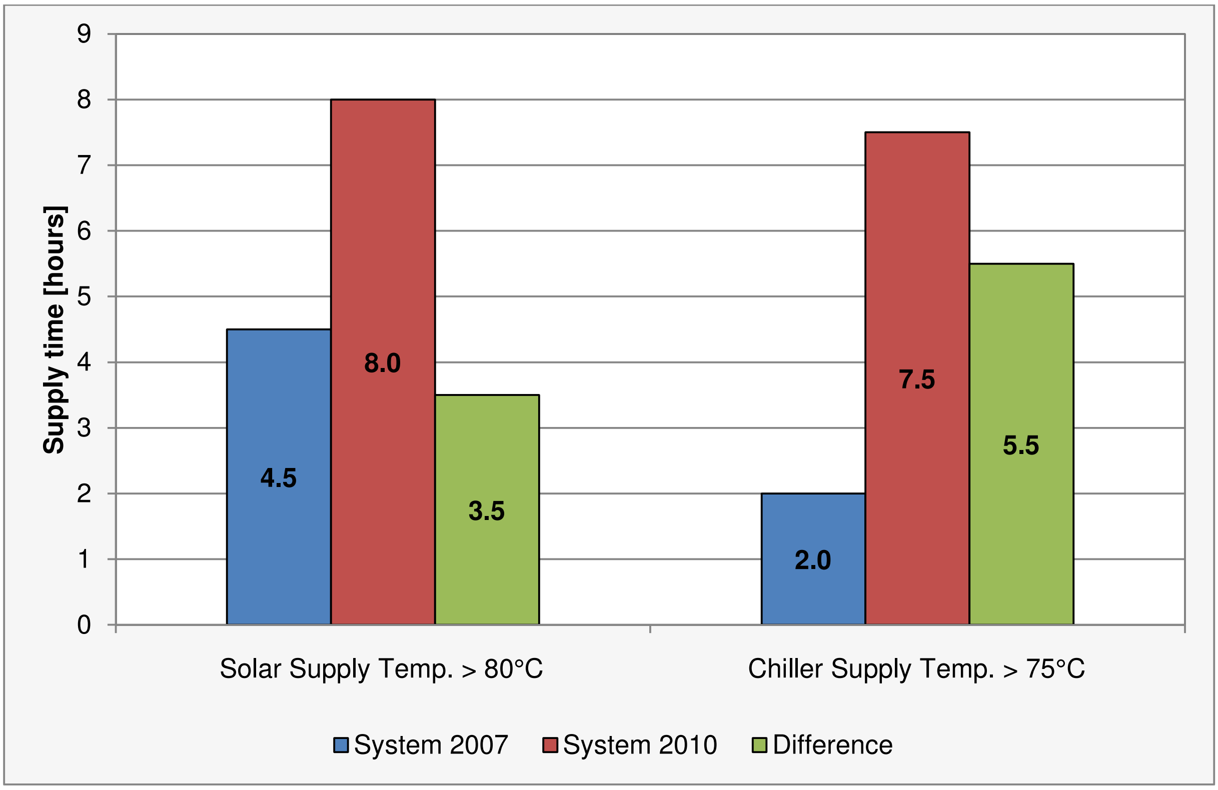


Figure 8-5: Comparison of useful temperature availability

The instantaneous solar heat supply at a useable temperature, leads to a simultaneous and sufficient supply for the sorption chiller. The 2010 system provides this temperature of 75°C for 7.5 hours compared to 2 hours for the 2007 system (see Figure 8-5). In summary, target temperature control applied by the 2010 system leads to a significant improvement of the sorption chiller operation conditions by continuously providing a sufficient solar supply temperature for driving the sorption process.

8.3 Comparison of energy sums

In Figure 8-6 the thermal output of the solar thermal plant is shown. The total output of the thermal plant with the 2010 system (157.4 kWh/day) is 15% lower compared to the 2007 system (186.2 kWh/day), mainly resulting from a lower output of the vacuum tubes. The reduced thermal output of the flat plate collectors by approximately 4% is caused by a higher average collector temperature resulting from the new control strategy of the 2010 system. The vacuum tube collectors are expected to have a lower sensitivity at higher operating temperatures. In this case, the reduced thermal output of the vacuum tubes is caused by a loss of vacuum in several tubes and dust on the rear reflection panel.

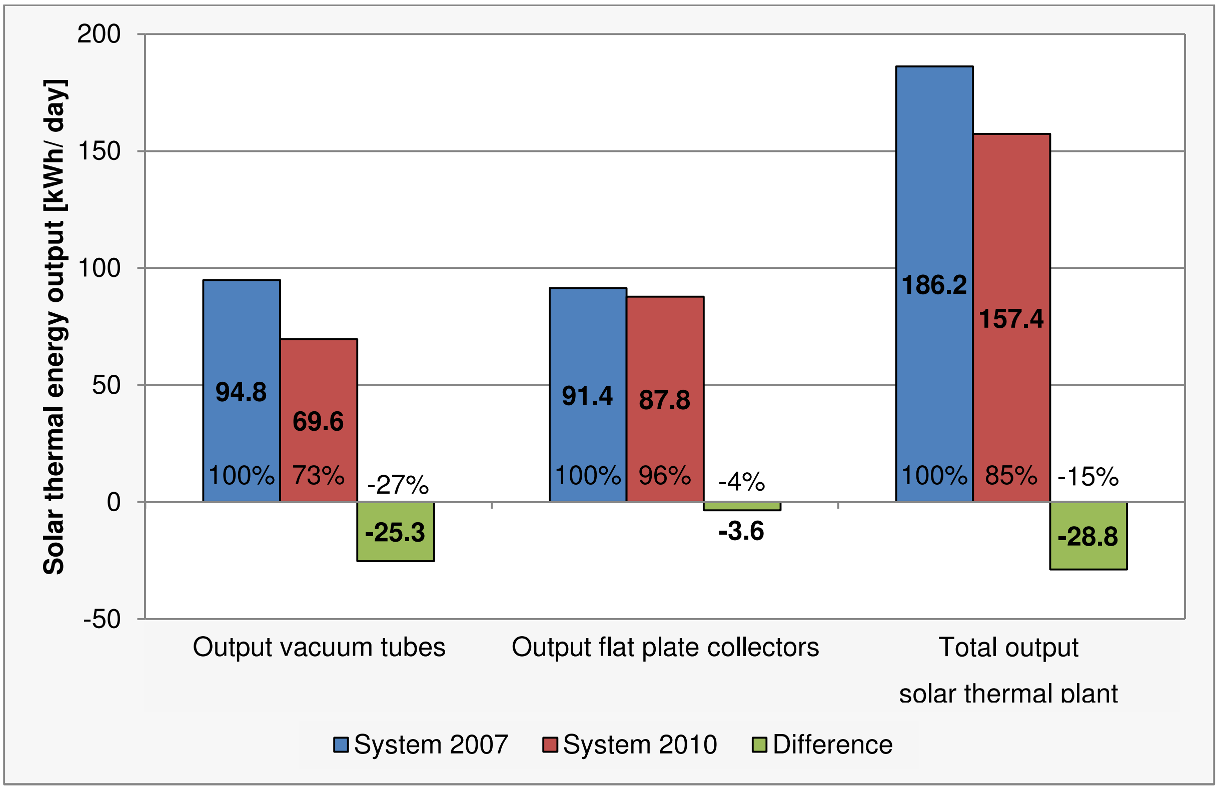


Figure 8-6: Solar thermal plant – Comparison of energy sums

The solar heat supply for the chiller (156.5 kWh/day), as well as the cooling output (102.5 kWh/day), is higher using the redesigned 2010 system. This is because almost all of the solar output of the 2010 system (157.4 kWh/day) can be used for cooling (Figure 8-7).

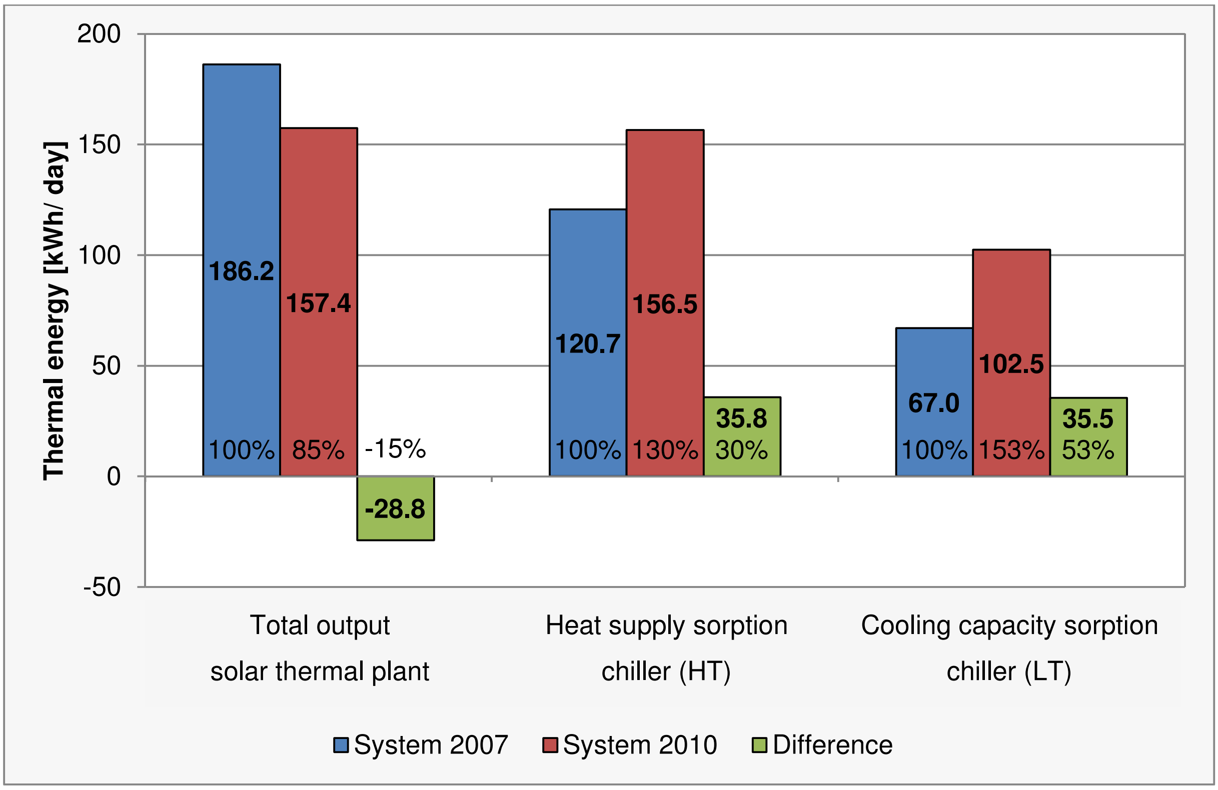


Figure 8-7: Solar cooling system – Comparison of energy sums

Compared to the 2007 system, the redesigned plant achieves a 53% higher cooling output, resulting from a 30% increase in solar heat supply with a 15% reduction in solar thermal output. To describe the benefits of the 2010 system relative to the 2007 system, new performance metrics are used (Figure 8-8).

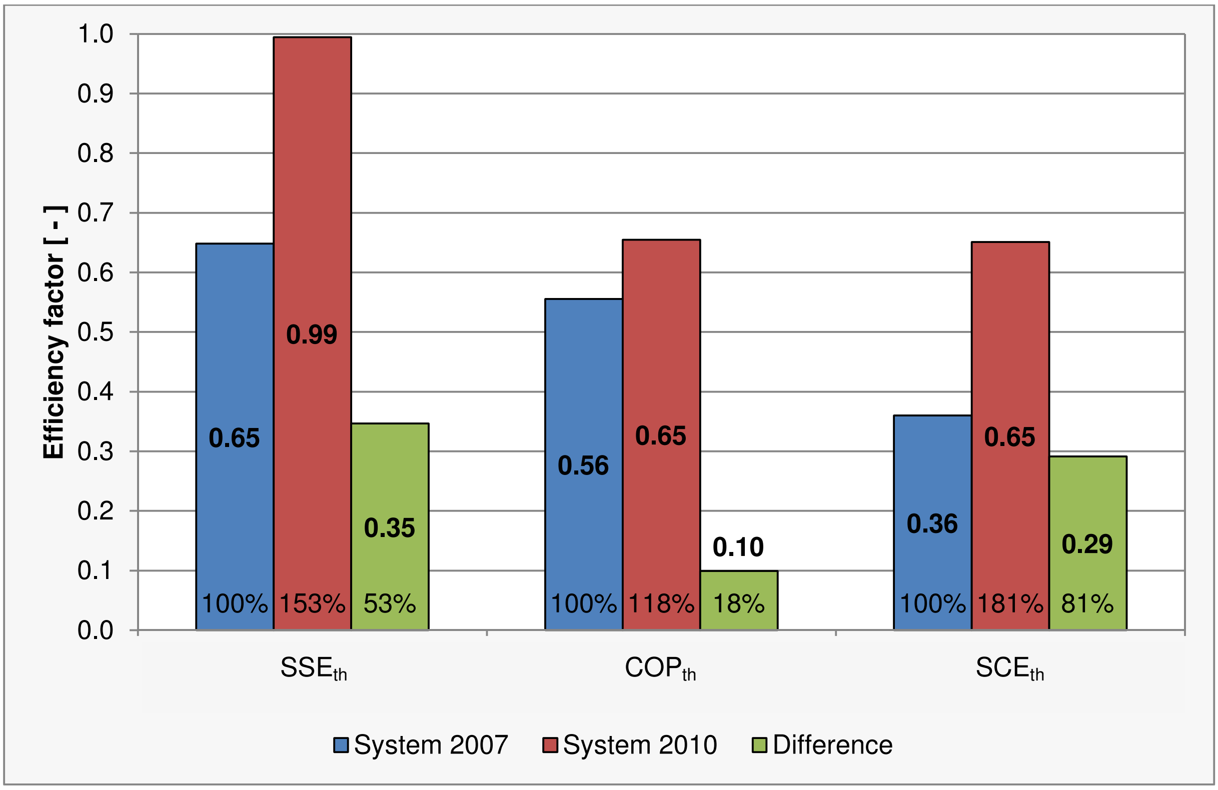


Figure 8-8: cooling system – Comparison of efficiency factors

The Solar Supply Efficiency (SSE_{th}) factor is the ratio of direct usable solar energy to total solar output. With the 2010 system, the SSE_{th} is increased by 53%. The product of the SSE_{th} and the COP_{th} gives the Solar Cooling Efficiency (SCE_{th}) factor. This efficiency factor describes the ratio of cooling output to total solar output. Combined with an 18% higher COP_{th}, the SCE_{th} of the 2010 system is 81% higher compared to the 2007 system.

Using the SCE_{th}, the performance of solar cooling systems can be illustrated clearly (e.g. Figure 8-9). In this example, although there is a reduction in the total solar thermal output, when combined with the improved SCE_{th}, a significant increase in cooling output can be achieved.

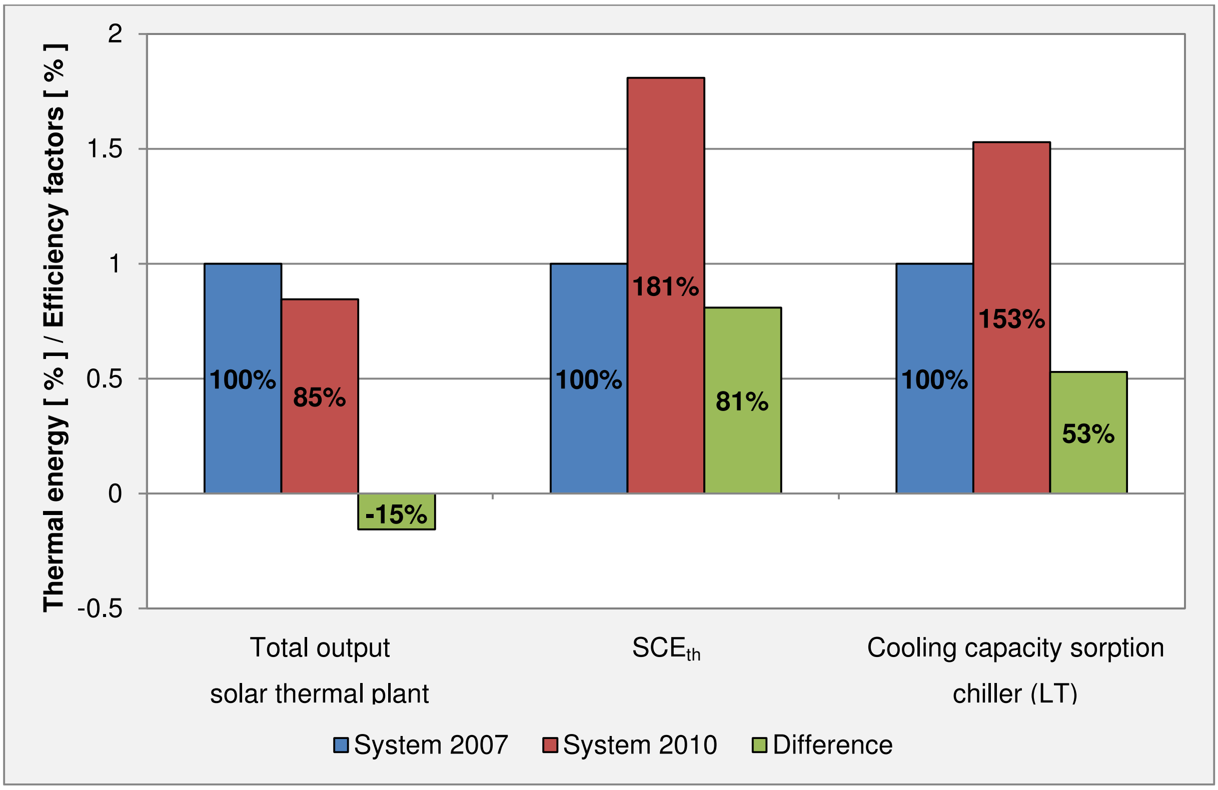


Figure 8-9: Solar cooling system – Relative comparison of systems

The measured performance and newly calculated efficiency factors are summarised in Table 8-2.

Table 8-2: Comparison of System 2007 with System 2010

System specification			System 2007	System 2010
Solar thermal plant	Heat output flat plate collectors	[kWh/d]	95	88
	Heat output vacuum tubes	[kWh/d]	91	70
	Total Heat output solar system	[kWh/d]	186	157
SSE_{th}	**Solar Supply Efficiency**	**[-]**	**0.65**	**0.99**
Sorption chiller	Heating input (available heat)	[kWh/d]	121	157
	Cooling output	[kWh/d]	67	102
COP_{th}	**Coefficient Of Performance**	**[-]**	**0.56**	**0.65**
SCE_{th}	**Solar Cooling Efficiency**	**[-]**	**0.36**	**0.65**

The SSE_{th} factor describes the quality of the solar generated heat by representing the percentage of directly useable thermal energy available for other processes. The product of the SSE_{th} with the COP_{th} of the chiller leads to the SCE_{th} factor which, for the first time, provides a clear and concise benchmarking system for the design of solar cooling systems.

Figure 8-10 shows a scatter plot of daily efficiency factors from system 2010 depending on the available amount of driving heat. During the 10-days operation period in July 2010 the system was only supplied with heat from the solar thermal system, including days with no heat supply for the absorption chiller, resulting from intermittent solar irradiation.

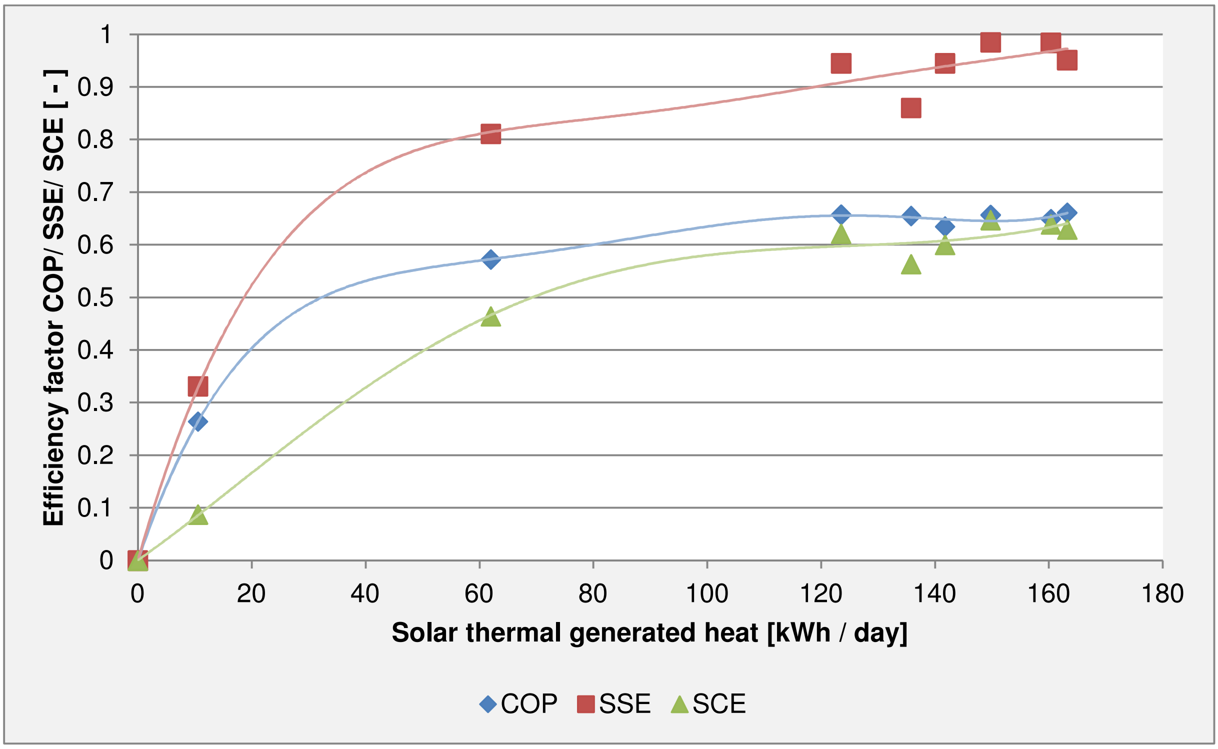


Figure 8-10: Efficiency factors of System 2010 - 10-days scatter plot (July 2010)

As illustrated in Figure 8-10, the system's efficiency clearly decreases with shorter operation periods resulting from relatively higher losses, such as losses for preparing operation conditions (e.g. heat up active storage mass and piping) and higher heat losses caused by longer standby periods.

8.4 Comparison with other solar cooling systems in the field

Within this section, the optimized 2010 system is compared with other solar cooling systems in the field (Systems A and B), using the performance metrics SSE_{th}, COP_{th} and SCE_{th}.

In 2012, Martinez presented performance data of a solar cooling system, consisting of flat-plate collectors (38.4m²) charging a 1000 l heat storage tank, and a Yazaki WFC-SC5 absorption chiller for providing the cooling load via a cold storage tank (Martínez et al. 2012). In Table 8–2, his presented average daily energy sums (System A) are compared with the 2010 system.

Table 8-3: Comparison of System A with System 2010

System specification			System A	System 2010
Solar thermal plant	Heat output flat plate collectors	[kWh/d]	75	88
	Heat output vacuum tubes	[kWh/d]	-	70
	Total Heat output solar system	[kWh/d]	75	157
SSE_{th}	**Solar Supply Efficiency**	**[-]**	**0.61**	**0.99**
Sorption chiller	Heating input (available heat)	[kWh/d]	46	157
	Cooling output	[kWh/d]	31	102
COP_{th}	**Coefficient Of Performance**	**[-]**	**0.69**	**0.65**
SCE_{th}	**Solar Cooling Efficiency**	**[-]**	**0.42**	**0.65**

Comparing the plant configurations of System A and System 2010 shows that subsystems and components are similar. For example, both systems have a solar thermal system consisting of flat plate collectors charging the storage via a plate heat exchanger and supplying the identical Yazaki absorption chiller. Figure 8–10 shows the comparison of both systems, applying the thermal performance metrics SSE_{th}, COP_{th} and SCE_{th} for illustrating the daily efficiency.

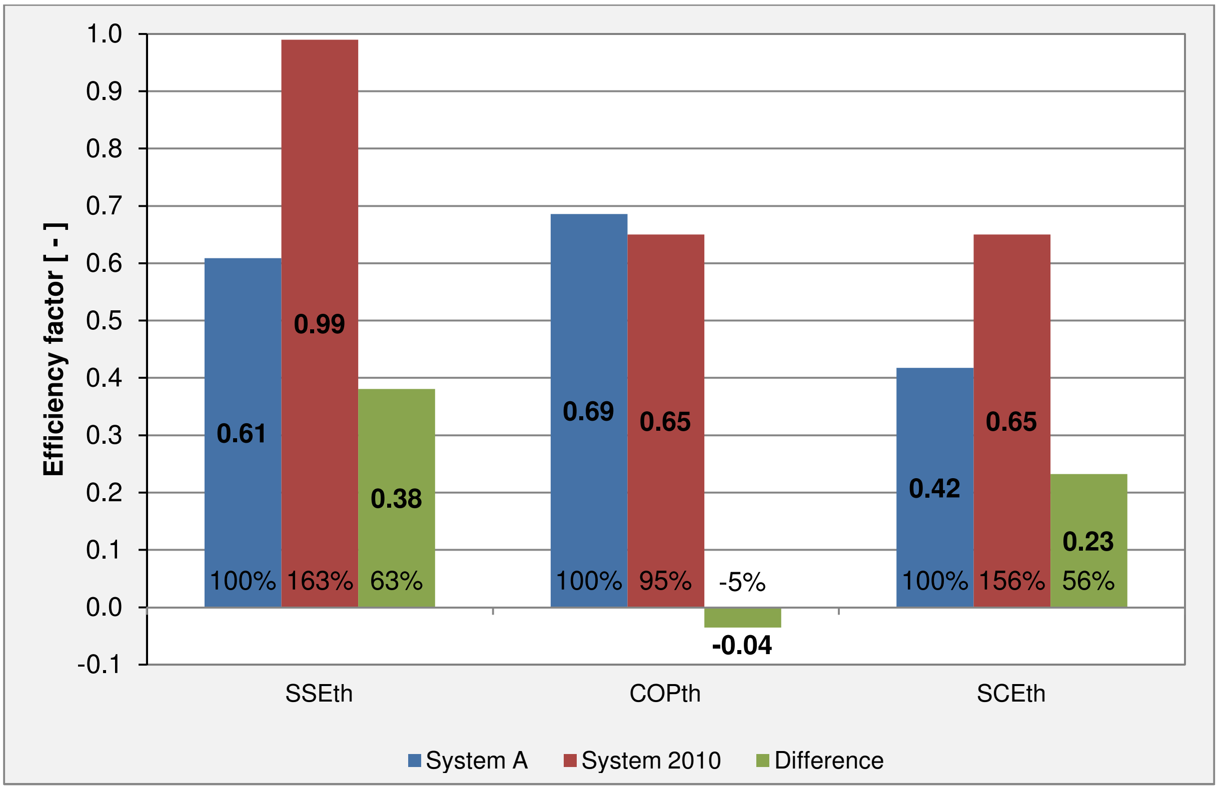


Figure 8-11: Solar cooling system – Comparison of daily efficiency (System A – System 2010)

The SCE_{th}=0.65 of the 2010 system is 56% higher compared with the SCE_{th}=0.42 of the solar cooling system in Spain (System A). This results from a 63% increased SSE_{th} factor combined with a 5% decreased COP_{th} of the absorption chiller. Regarding the delivered information from Martinez (Martínez et al. 2012) leads to the assumption that the presented System B is only focused on optimized operation of the absorption chiller but not on efficient operation of the entire system. When considering given performance and temperature curves, System A generates solar thermal heat from 10 a.m. until 6 p.m. (8 hours), whereby the absorption chiller operates from 1 p.m. until 5 p.m. (4 hours). This deviation indicates that heat generation is not demand-oriented leading to a late start-up of the chiller caused by a pre-heating phase of the storage system. Furthermore, the operation of the subsystems seems not to be harmonized which causes discontinuous operation of the chiller (start & stops) resulting from differing mass flows of heat generation and demand. It is assumed that System A does not provide a sufficient heat supply nor is equipped with an optimised storage charging and discharging system leading to a significant lower SSE_{th} factor compared with System 2010.

Ayadi presents measurement results of a solar cooling system designed for an office building in Italy (Ayadi et al. 2012). The system consists of flat-plate collectors (61.6m²) charging a 5000 l heat storage and supplying a Yazaki WFC-SC5 absorption chiller for providing the cooling load via a 1000 l cold storage tank. In Table 8–3, the presented data of June (System B) is compared with measurement data of June from the 2010 system, applying performance metrics calculated monthly.

Table 8-4: Comparison of System B with System 2010

System specification			System B	System 2010
SSE_{th}	**Solar Supply Efficiency**	**[-]**	**0.55**	**0.89**
COP_{th}	**Coefficient Of Performance**	**[-]**	**0.52**	**0.65**
SCE_{th}	**Solar Cooling Efficiency**	**[-]**	**0.29**	**0.58**

Figure 8–11 shows the performance metrics SSE_{th}, COP_{th} and SCE_{th}, illustrating the monthly efficiencies of both systems.

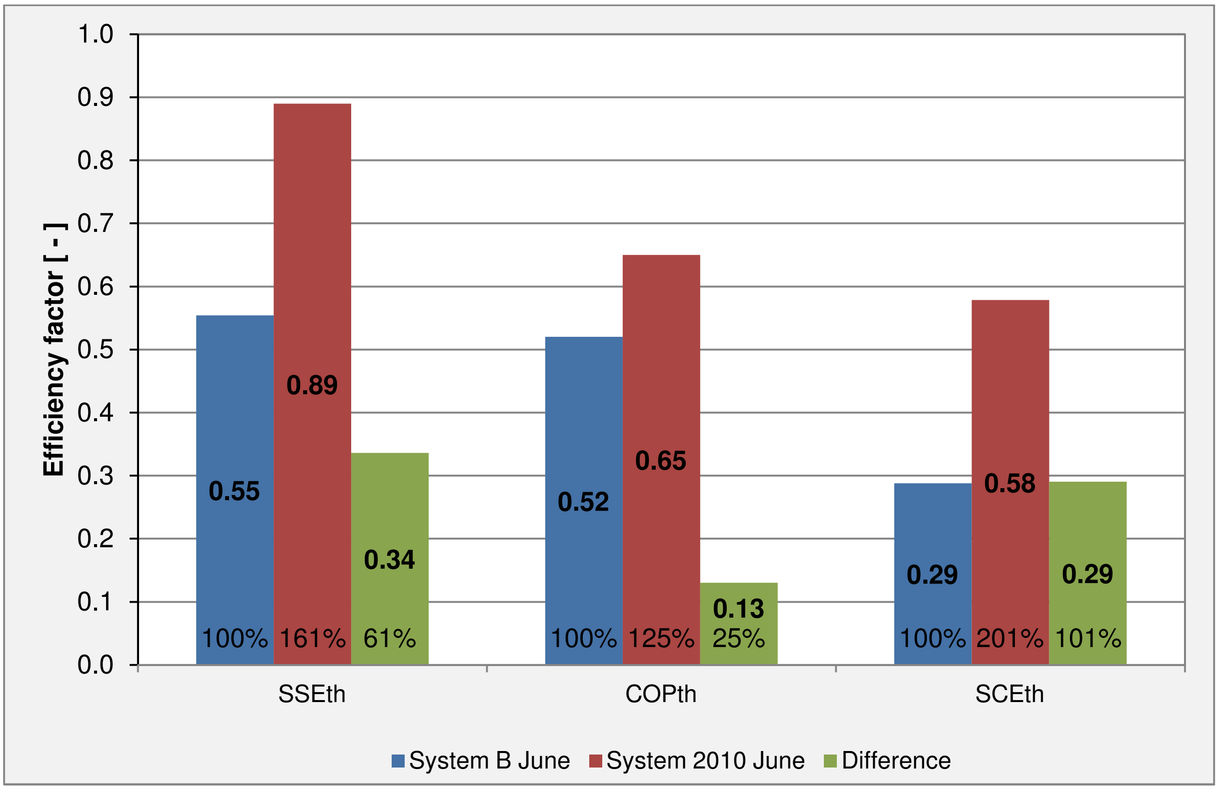


Figure 8-12: Solar cooling system – Comparison of monthly efficiency (System B – System 2010)

Combined with a 25% higher COP_{th}, the SCE_{th} of the 2010 system is 101% higher compared to the System B, mainly resulting from a 61% increased SSE_{th} factor.

Figure 8-10 shows a scatter plot of daily efficiency factors from System 2010 depending on the available amount of driving heat. In June, the system was operated solar-assisted, being supplied via heat from the solar thermal system (49%) and the oil-fired boiler.

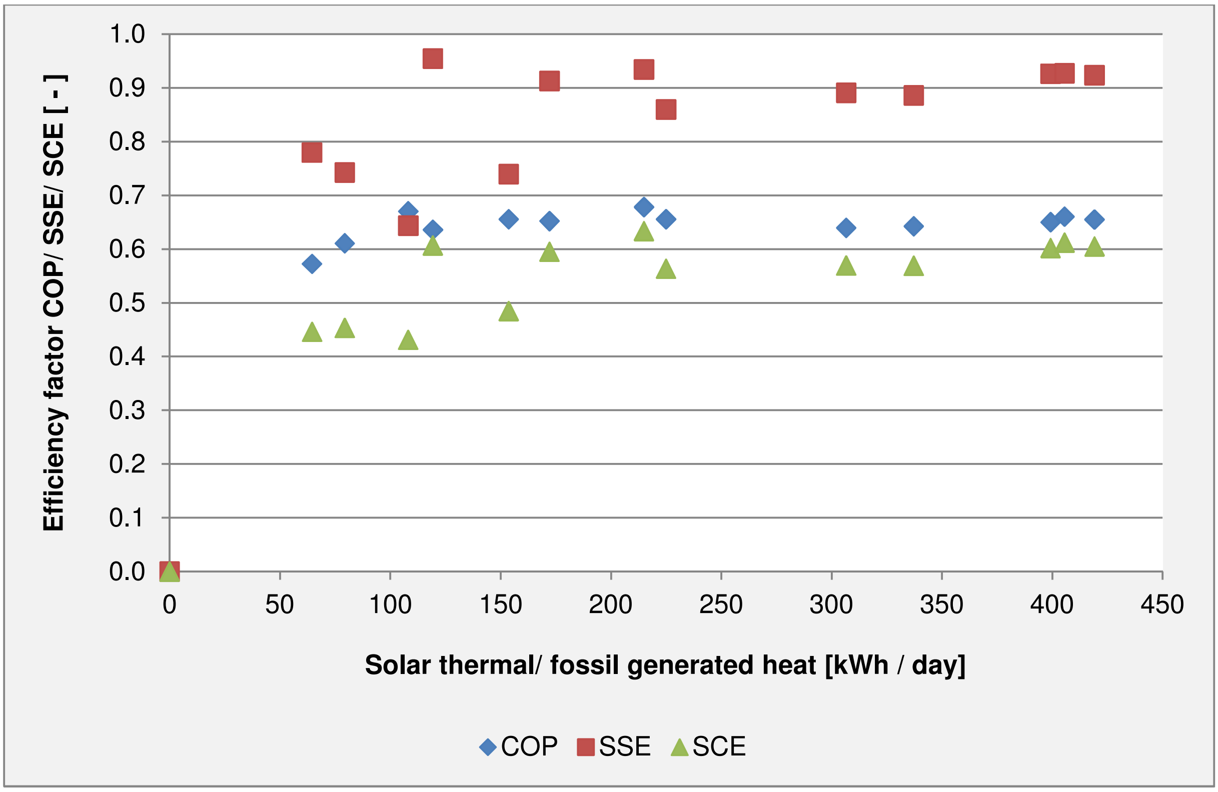


Figure 8-13: Efficiency factors of System 2010 - scatter plot (June 2010)

In Summary, the redesigned System 2010 is significantly more efficient compared to System 2007 and the considered systems in the field. The consequently applied system perspective for design led to focus on the amount of usable heat that enables a more efficient operation of the entire system.

8.5 Summary

This chapter described the validation of the generic design for solar cooling systems via novel performance metrics. By comparison of measurement data from the 2007 pilot plant against data from the redesigned 2010 system, improvements from the novel design led to an 81% higher SCE_{th} compared to the former system. As the new system is based on demand-oriented target temperature control rather than traditional, temperature difference control, this method was found to be very successful as it enabled the sorption process to be started as soon as the solar thermal heat generation commenced. Consequently, the availability of the energy to drive the cooling process coincided with the demand for cooling (from 9:30 – 18:00). This is in contrast to the former system in which there is a temporal conflict between the ability to supply cooling and the requirement for cooling. Measurements from the new system showed that this new strategy can yield a 53% increase in cooling output (102.5 kWh/day) compared to the old system (67.0 kWh/day). Although the solar thermal output of the new system during the measurement period was 15% lower (157.4 kWh/day) than the old system (186.2 kWh/day), the heat supply to drive the chiller was 30% higher. Thus, in combination with the 18% increase of the sorption process COP_{th} factor, this leads to an 81% increase of the Solar Cooling Efficiency factor - SCE_{th}.

Recent measurement data from comparable sorption systems within the field, yield a daily SCE_{th}=0.42 (Martínez et al. 2012) and a monthly SCE_{th}=0.29 (Ayadi et al. 2012). In comparison, with a daily SCE_{th} =0.65 and a monthly SCE_{th} =0.58, the optimized 2010 system delivers a 56-101% higher SCE_{th} factor, confirming the significant improvement of the solar cooling system’s efficiency achieved by this work.

9. Market available products

9.1 Preamble

The purpose of this chapter is to show how scientific findings and experiences from this work have been transferred to the market. The validation of the novel design has delivered an 81% higher efficiency compared to the former solar cooling system configuration of the 2007 pilot plant. Investigated characteristics for high efficient solar cooling systems firstly leads to the novel chillii® System Controller, including innovative operation strategies such as target temperature control. Secondly, based on an adequate system controller, preconfigured sorption subsystems - the chillii® Cooling Kits - are developed. Thirdly, the engineering product chillii® System Design ensures the implementation of the recommended generic design characteristics, completing the product portfolio for optimized solar cooling systems. Within the following sections, the market available products resulting from this work are presented.

9.2 chillii® System Controller

Based on the generic design for solar cooling systems, the chillii® System Controller (see Figure 9-1) has been developed to operate the entire thermal energy system. To enter the heating and cooling market with this product, two controller versions are available: The chillii® System Controller H for pure heating applications and the chillii® System Controller HC for heating and cooling purposes.

Figure 9-1: chillii® System Controller (Source: SolarNext AG)

Covering a variety of solar cooling applications requires a control system which enables customized thermal system configurations. This includes the possibility of operating several types of actuators such as pumps, fans and mixers. In addition, the common market-available heat sources, chiller types and heat distribution circuits must also be controlled. With Table 9-1 illustrates the technical specifications of the chillii® System Controller.

Table 9-1: Technical data of the chillii©System Controller (Source: SolarNext AG)

Technical Data chilli©System Controller		
Overview	Supply voltage [V]	110 – 230 V
	Supply frequency [Hz]	50 – 60 Hz
	Weight [kg]	a. kg
	Dimensions (WxHxD) [mm]	285 x 352 x 96 mm
	Power consumption [W]	< 14W
Hardware (Inputs)	39 x	PT 1000 temperature sensors
	2 x	NTC temperature sensors
	7 x	Digital inlets, potential-free
	4 x	Inlets, voltage detection
	1 x	Impulse inlet
Hardware (Outputs)	13 x	Outputs for pumps, 230V , 600VA
	11 x	Analogue outputs 0-10V
	29 x	Switching outlets 230V, mixers, pumps
	9 x	Switches potential-free
	3 x	Analogue outlets 0-10V/ 0-20mA
Display	Illuminated touch screen	
Interfaces	Network	RJ-45 Ethernet-Port
	Data storage	SD-card slot with card detection
	CAN-Bus	D-Sub-bushing, 9 poles

The hardware specifications show a high number of I/O’s for sensors and actuators such as PT1000 temperature sensors, analogue outputs for speed controlled electric drives and several switches to include all sorts of market available components. An integrated configuration guide ensures a good usability while customizing the control system for the specific plant to implement. Via an onboard SD-card slot, system configurations can be up- and downloaded, enabling an easy pre-configuration via technicians or directly by the customer. An onboard Ethernet interface integrates the controller into the local network for remote control and service tasks. For optimization and documentation purposes, the chillii® System Controller provides an onboard data logger as well. In Summary, the control characteristics deliver good conditions for operating various components and subsystems while ensuring a good usability.

9.3 Cooling Kits

For minimizing engineering effort and maximizing reliability, preconfigured sorption subsystems have been developed. Enabled by the chillii® System Controller, different chillii® Cooling Kits for a wide range of applications have been designed. This includes different sorption technologies as well as different heat rejection systems and various onsite specifications. The chillii® Cooling Kits are designed as modular subsystems with alternative extensions to be integrated in thermal systems, leading to a customised solar cooling system.

9.3.1 COP$_{con}$ for sorption chiller subsystems

For direct performance comparison with traditional compression technology, the COP$_{con}$ is calculated for each chillii® Cooling Kit, rating irreversibilities resulting from energy conversion [see Equation (9-1)].

$$COP_{con\,el\,sorp} = COP_{th\,sorp} \cdot f_{con\,sorp} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \cdot \frac{\dot{Q}_{HT} + \dot{W}_{el\,aux}}{\dot{W}_{el\,aux}} \qquad (9\text{-}1)$$

Recall that for sorption subsystems, f_{con} is a specific value depending on the sorption chiller type and the auxiliary components such as heat supply, cold distribution and heat rejection. For each chillii® Cooling Kit, there are two system configurations considered. Subsystem 1 (see Figure 9-2) is operated with an active heat rejection device such as a wet cooling tower, a dry cooler or a hybrid cooler.

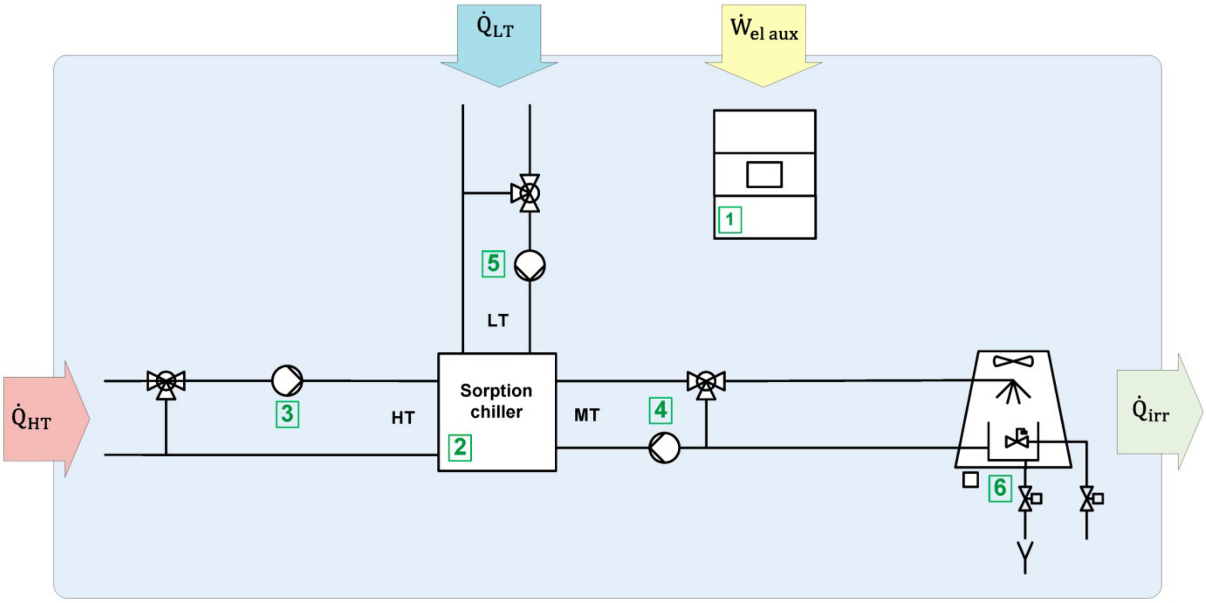


Figure 9-2: Sorption chiller subsystem 1 – active heat rejection

Subsystem 2 illustrated in Figure 9-3, is operated via a passive heat rejection system such as a natural ground water heat sink, a preheating system for domestic hot water or a swimming pool.

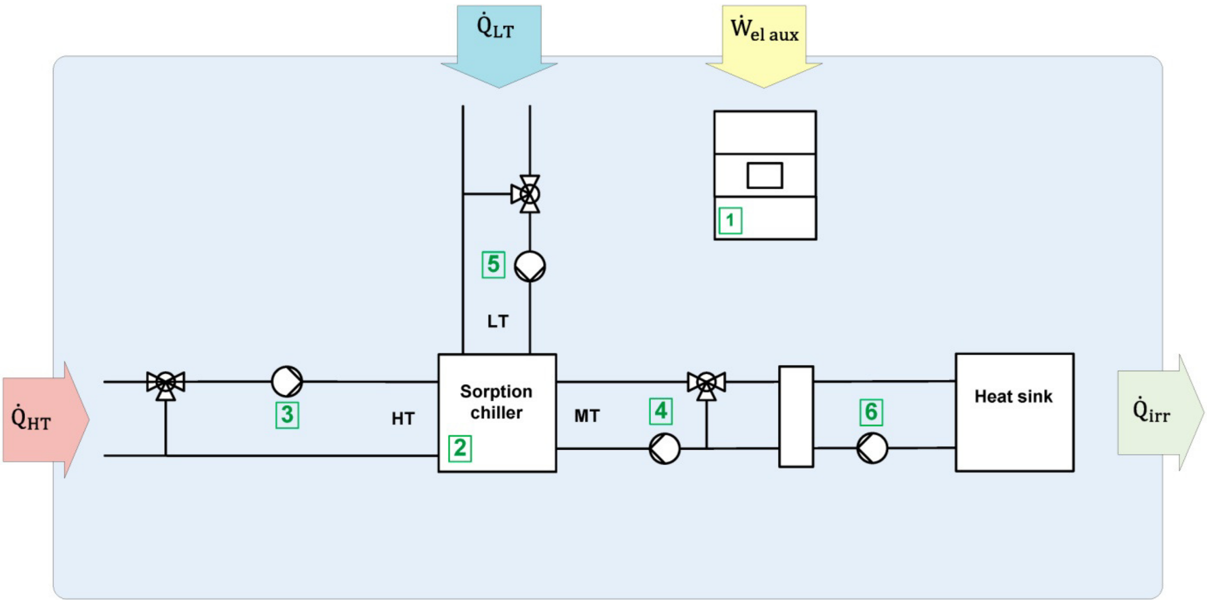


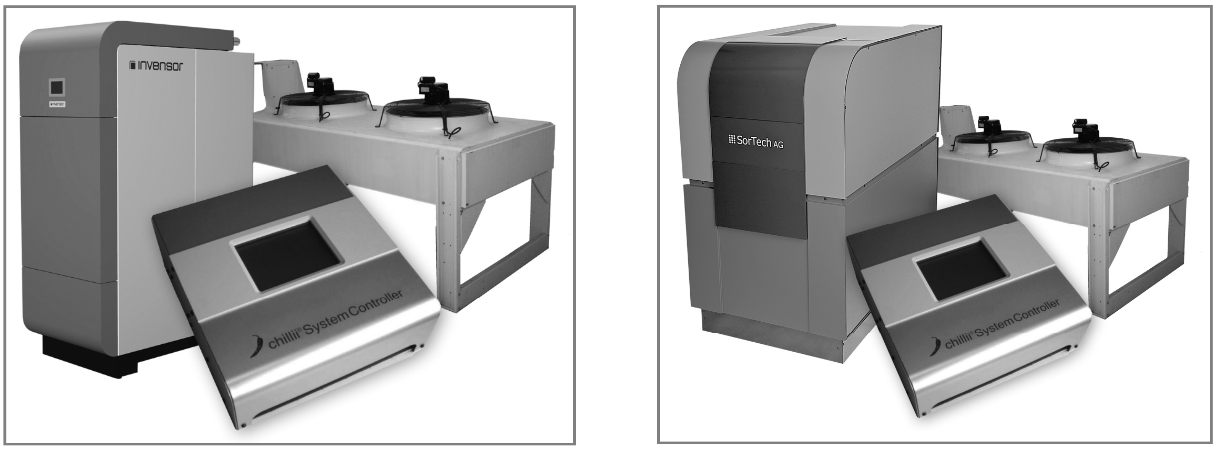
Figure 9-3: Sorption chiller subsystem 2 – passive heat rejection

The calculation of $COP_{con\ el\ sys\ 1}$ and $COP_{con\ el\ sys\ 2}$ is processed via a $\dot{W}_{el\ aux}$ including the electrical power consumption of all components within the subsystem (see 1-6 in Figure 9-2 and Figure 9-3). To avoid confusion by various onsite structures, the pressure drops resulting from piping are not included when calculating the operation points of the systems. Different groups of sorption cooling subsystems are developed, each optimized for a specific range of cooling applications.

The chillii® Cooling Kits presented within the following sections were available on the market in 2010. Some of them are no longer available, because integrated sorption chillers have been replaced by newer models (e.g. chillii® Cooling Kit PSC12 is replaced by chillii® Cooling Kit PSC19).

9.3.2 chillii® Adsorption Kits

The chillii® Adsorption Kits (SolarNext AG 2010) are designed for cooling applications with a cold water supply temperature around 15°C, and low driving heat temperatures with minimum 45°C (see Figures 9-4). These characteristics are suitable for cooling of small to medium buildings via cooled ceilings or floor cooling systems (up to 150m² depending on specific cooling load per m² of onsite structures).



Figures 9-4: chilli© Cooling Kits ISC 10 and STC15 (Source: SolarNext AG)

Figure 9-5 illustrates the traditional thermal efficiency factor COP_{th}, and the novel performance metrics $COP_{con\ el\ sys\ 1}$ and $COP_{con\ el\ sys\ 2}$, including the irreversible conversion of electricity to drive the system. Recall, that sys1 is a subsystem operated with an active heat rejection system such as a cooling tower, and sys2 is a sorption subsystem using a passive heat rejection such as a natural ground water heat sink (see section 9.3.1.). The thermal COP is relevant for designing the heat supply by defining the required performance of the heat sources. The conversion COP's are metrics for comparison with compression technology and for evaluating the efficiency of different subsystem configurations. For the chillii® Adsorption Kits, the COP_{con} increases with the cooling capacity of the sorption subsystems being considered, mainly resulting from a lower ratio of electricity consumption. Considering different heat rejection methods, leads to a higher efficiency when using passive heat sinks ($COP_{con\ el\ sys\ 2}$) compared to active heat rejection methods ($COP_{con\ el\ sys\ 1}$) via cooling towers. Recall that energy consumption resulting from pressure drops of piping is not included within this calculation. This task is covered by the system designer when customizing the specific cooling kit.

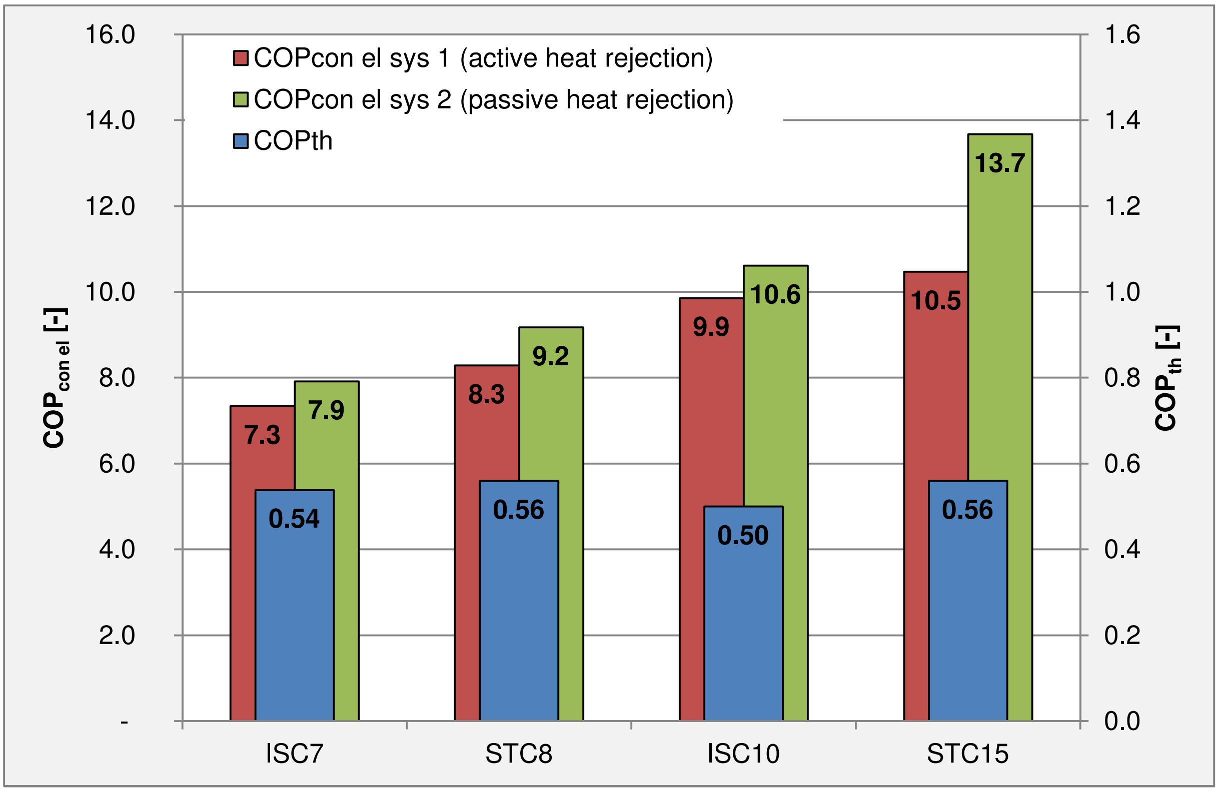


Figure 9-5: Adsorption kits – comparison of performance metrics

9.3.3 chillii® Absorption Kits (LiBr)

The chillii® Absorption Kits (LiBr) (SolarNext AG 2010) with the working pair lithium-bromide and water are designed for cooling applications with a cold water supply temperature with minimum 6°C, and driving heat temperatures from 70°C to 95°C (see Figure 9-6). These characteristics make those kits suitable for cooling purposes with fluid-air heat exchangers such as fan coils.

Figure 9-6: chilli© Cooling Kits WFC18 and WFC35 (Source: SolarNext AG)

The performance metrics of the chillii® Absorption Kits (LiBr) are shown in Figure 9-7. Compared with adsorption technology, a higher thermal COP leads to less heat supply while requiring a higher temperature to drive the absorption systems. Regarding kits with comparable cooling capacities (e.g. STC15 compared to WFC18), deliver similar COP_{con}s.

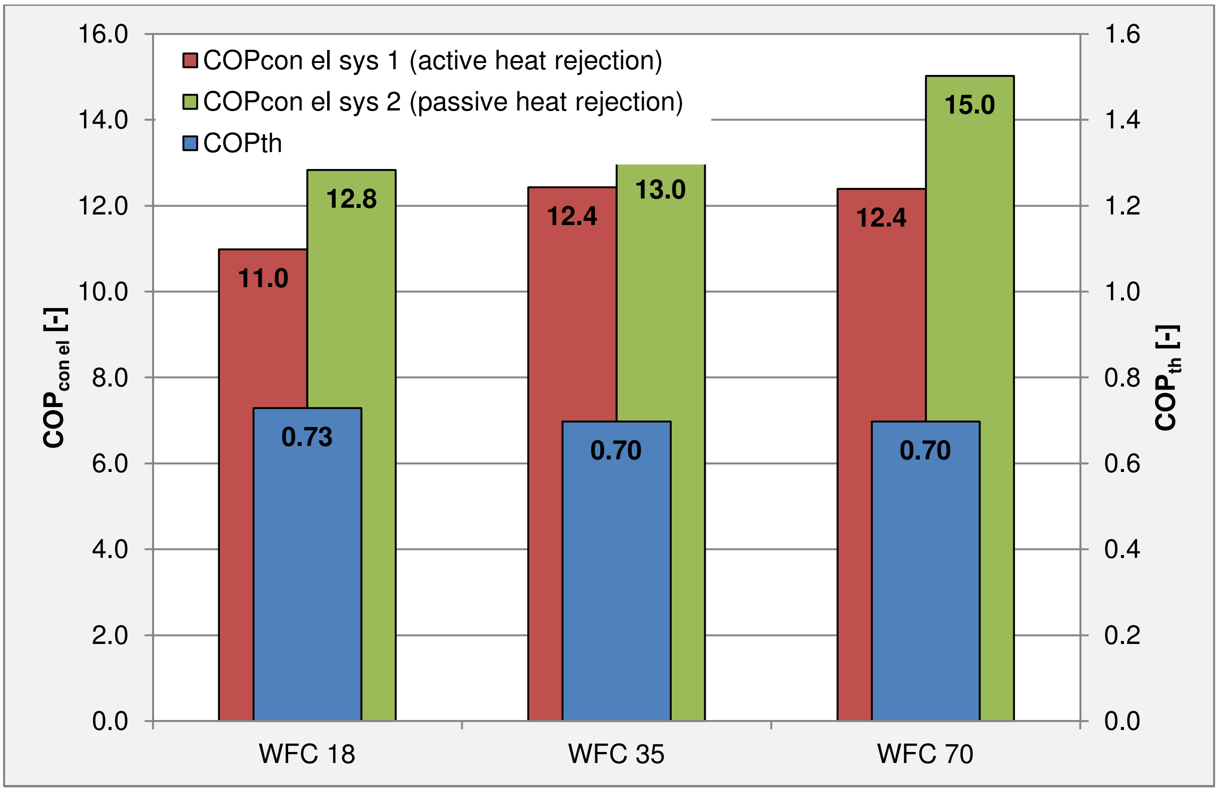


Figure 9-7: Absorption kits LiBr – comparison of performance metrics

9.3.4 chillii® Absorption Kits (NH_3)

The chillii® Absorption Kits (NH_3) (SolarNext AG 2010) with the working water and ammonia are designed for cooling applications with a cold water supply temperature down to - 10°C requiring driving heat temperatures from 70°C to 120°C. This cooling temperature is suitable for freezing applications or food cooling. When operating the sorption system with temperatures over 95°C, the economic effort for implementation increases significantly, as common hydraulic components are designed and certified for maximum 95°C. Firstly, this leads to more expensive components, and secondly stricter standards and regulations have to be applied, which generates more engineering effort. Figure 9-8 illustrates the performance metrics of the chillii® Absorption Kits (NH_3).

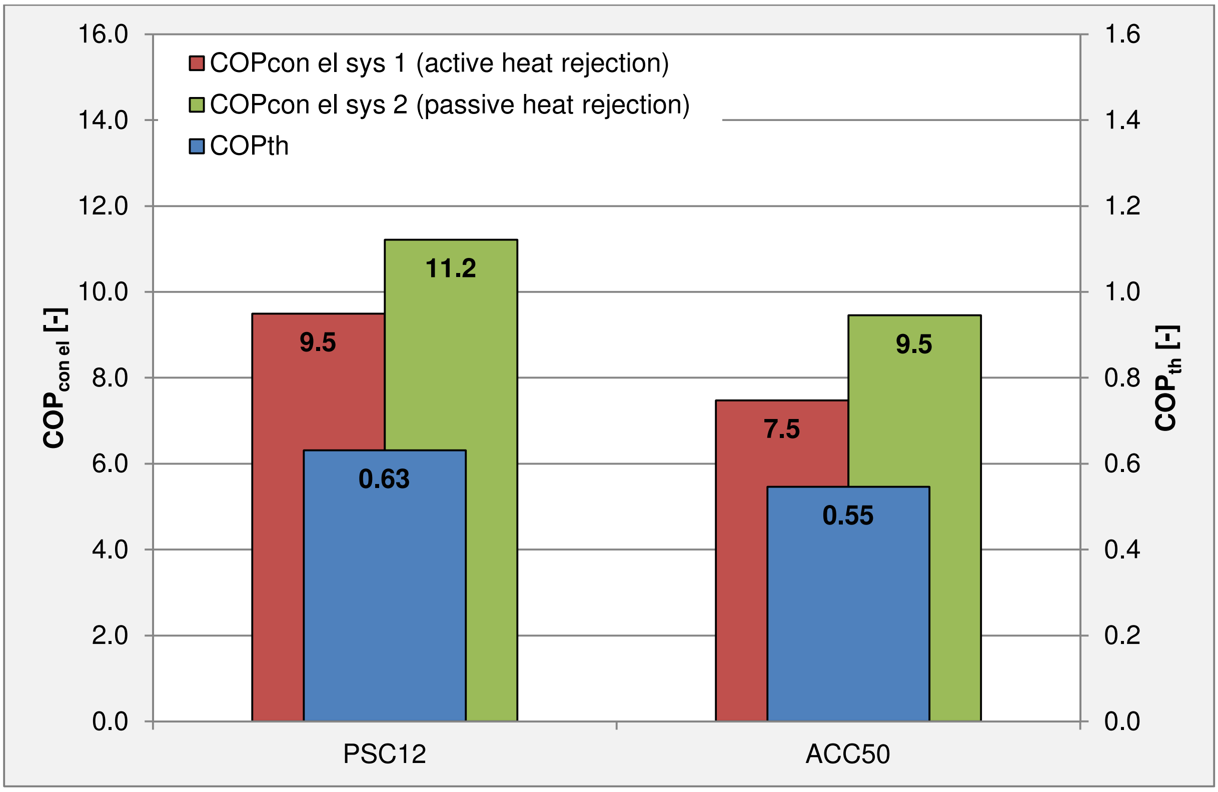


Figure 9-8: Absorption kits NH_3 – comparison of performance metrics

9.4 chillii® System Design

The chillii® System Design (SolarNext AG 2010) covers the remaining engineering effort for integrating the sorption subsystem and completing the solar cooling system. This task includes the design of adequate piping for low pressure drops and a high COP_{con} as well as the configuration of heat sources and distribution circuits.

The general methodology starts with specifying the demand via fluid temperatures, periodic heating and cooling loads and the amount of energy required. These parameters combined with onsite conditions such as climate and local building structures, leads to specification of fundamental characteristics of the thermal energy system under consideration. With adequate heating and cooling circuits for covering the demand, the basic sorption subsystem can be chosen and configured in detail. The resulting heat demand leads to the design of the involved heat sources such as the solar thermal plant, biomass or fossil boilers. During this procedure, the dimensions of heat and cold stores are also fixed.

Existing thermal systems to be extended using a sorption cooling system require more design and engineering effort than new systems, as existing components and hydraulics often have to be optimized to ensure reliable and efficient operation.

9.5 Summary of market available products

This chapter described market available products as a result of scientific work guided by the theory of nested systems and being transferred to product development. By developing the chillii® System Controller, several sorption cooling kits could be configured leading to optimized engineering effort and maximised reliability and efficiency. The complex product “solar cooling system” was transferred to modular products with alternative configurations and extensions. With the chillii® System Controller, various components can be operated while ensuring maximum usability via only one human interface for control. With the chillii© System Design and the preconfigured cooling kits, engineering and investment efforts are reduced and the implementation of optimized solar cooling systems can be ensured.

10. Conclusions

10.1 Summary of contribution to knowledge

This work has closed the gap between research and market-readiness of the working principle “solar thermally driven cooling”. This was achieved by generating guidance through the whole research procedure via the newly developed methodology for investigating complex structures – the theory of nested systems. With novel and established methods for analysis and design, essential short-comings of solar cooling systems have been identified and overcome by technical and economical optimization.

This research work applied the EntropyGenerationMinimization-method (EGM-method) for pure thermal processes, leading to a thermodynamic optimized generic design for heating and cooling systems. Furthermore, this research work defined new performance metrics for benchmarking thermal systems such as the SSE_{th} and the SCE_{th}. By considering energy conversion irreversibilities, a coefficient of performance metric was defined, firstly enabling a direct comparison of sorption cooling systems with compression chiller systems. The scientific findings from this work were successfully transferred to the development of a new control system leading to an 81% higher Solar Cooling Efficiency (SCE_{th}) compared to the former system. The investigated results were applied to design modular sorption cooling kits which led to a completed product portfolio for a wide range of solar cooling applications for the market.

10.2 Methodology for integrated research and systems engineering

This work delivered a new methodology for integrated research and systems engineering by combining holistic thinking with fundamental scientific methods and established engineering principles – *The theory of nested systems*.

The theory of nested systems is based on principles that describe the multi-dimensional systems under consideration. The main principles for describing multilayer systems within this theory are:

- each system includes subsystems which themselves consist of further parts;
- all systems interact with each other; and
- the combination of systems leads to emerging effects.

This methodology includes natural and artificial systems as well as unchangeable and designable aspects generating a specific model that represents the structure of surrounding and integrated systems. For identifying and describing correlations between the several dimensions, the theory of nested systems allows bottom-up and top-down interaction, which may consist of direct dependencies between the systems and/or chains of direct correlations between several system levels. The application of this novel methodology for this work enabled an efficient and concise procedure for analysis and design without over sizing the system under consideration. Furthermore, by combining a multilayer approach with a target oriented model, new scientific methods were established.

10.3 Novel methods for analysis and design of thermal systems

This work has produced novel methods for analysis and design of thermal systems. The HeatDistributionCooling-modelling (HDC-modelling) supplemented with the GenerationLinkDemand-method (GLD-method), enables an optimized thermodynamic generic design with best conditions for coordination of all components.

The HDC-modelling delivers an informative heat flow chart of any considered thermal system, while describing structural correlations clearly. By classifying the main components of the thermal system under consideration to the segments HEAT, DISTRIBUTION and COOLING, a generic HDC-model is developed. This method is suitable for analysis as well as for the design of thermal systems.

Applying the GLD-method to the specific HDC-model of the thermal system identifies the overall system coordination, which leads to an abstract functional model of the considered system.

For this work, applying the HDC-modelling supplemented with the GLD-method for analysis and design, led to a generic design for highest efficiency and best coordination of solar cooling systems.

10.4 Thermodynamic optimized generic design of solar heating and cooling systems

The work delivered an optimized modular generic design for a wide range of heating and cooling applications. The generic design results from thermodynamic optimization including energy conversion via an integrated priority for renewable energy sources. This was achieved via combining a general energy concept with thermodynamic optimization of system architecture and best operation conditions for single components. The general energy concept includes optimization of demand, fossil and renewable energy generation as well as coordinated usage of stored energy. This process represents a systematic minimization of entropy generation for providing the energy supply of the entire system. Implementing the generic energy concept for system architecture led to a central role of the thermal storage and the thermodynamic optimization of the charging and discharging process. By applying the EGM-Method, general characteristics for best thermodynamic design of thermal storage and optimized operation of sorption chillers were developed and transferred to thermal design specifications.

For minimized irreversibility from charging and discharging the thermal storage, the supply flow temperatures of connected heat generation and heat consuming units were harmonized with demand-oriented target temperature control to minimize the temperature difference between. For achieving minimum entropy generation rate resulting from return flow temperatures, charging and discharging mass flows are controlled to achieve a minimum temperature difference. To minimize entropy generation resulting from mass, the active volume for preheating and operating the storage was reduced to a minimum depending on the actual charging level.

For reducing heat losses, firstly supply and return flow temperatures are reduced, considering temperature requirements of each application. Secondly, the active storage mass was reduced. The integration of EGM-characteristics was achieved by implementing demand-oriented target temperature control combined with a central thermal storage, representing an optimized configuration for solar cooling systems. The developed generic design represents a modular thermal energy system enabling an ongoing evolutionary optimization process, without having to reinvent the whole system.

10.5 New performance metrics for representative validation

This work has led to the definition of three new performance metrics for benchmarking the quality and performance of solar cooling systems. The Solar Supply Efficiency (SSE_{th}), the Solar Cooling Efficiency (SCE_{th}) and the Coefficient Of Performance including energy conversion (COP_{con}). With the new performance metrics SSE_{th} and SCE_{th}, the boundaries of the thermal validation of the solar cooling system investigated were extended compared with the existing methodology for evaluating the COP_{th}. The SSE_{th} is the ratio of the direct usable solar energy to the total solar output and the SCE_{th} represents the ratio of the cooling output to the total solar output. The SCE_{th} is equal to the product of the SSE_{th} and the COP_{th} of the chiller. The newly developed efficiency factors provide a method for obtaining realistic indicators of system quality and can be applied to nearly all solar cooling plants regardless of the method used for heat generation. Furthermore, the SSE_{th} enables an easy and concise rating for all thermal systems, benchmarking the heat flow linking between generation and demand, whether for pure heating or for heating and cooling applications.

Using the definition of COP_{con}, a validation method for direct comparison of sorption and compression chillers was developed. As those differing technologies represent substitution working principles for covering the same demand, a representative comparison method is essential for evaluating the specific application. Using the definition of the conversion factor f_{con}, the established COP_{th} for validating the thermal performance of sorption chillers is converted to a representative COP_{el} for validating compression chillers or vice versa. The conversion factor f_{con}, considers the application of electrical work for a thermal benefit, and therefore includes irreversible conversion efforts represented by the rate of entropy generation by this process. The $COP_{con\ el}$ is the product of the conversion factor f_{con} and the established COP_{th} of the sorption chiller, leading to a representative performance metric for direct comparison with the COP_{el} of compression chillers. This methodology can be applied to all heat-supply machines, which require a certain amount of electricity for driving the operating principle of the device or system. Furthermore, this method firstly includes the evaluation of applying different energy forms for a certain energy benefit.

10.6 Validated solar cooling systems for the market

This work has quantified the improved performance of a solar cooling system being redesigned while following the novel generic design. Measurements delivered an 81% increase of the SCE_{th} factor, representing a significant improvement in the performance of the solar cooling system.

Recent measurement data from comparable sorption systems within the field, yield a daily SCE_{th}=0.42 (Martínez et al. 2012) and a monthly SCE_{th}=0.29 (Ayadi et al. 2012). In comparison, with a daily SCE_{th} =0.65 and a monthly SCE_{th} =0.58, the optimized 2010 system delivers a 56-101% higher SCE_{th} factor. Scatter plots of daily efficiency factors (SSE_{th}, SCE_{th} , COP_{th}) were generated for solar thermal and fossil driven operation, leading to good results for part load behaviour and confirming the significant improvement of the solar cooling system's efficiency achieved by this work.

The scientific findings resulting from this work were successfully transferred to product development, leading to innovative products such as a novel system controller for heating and cooling applications with up to 43 billion hydraulic variants and preconfigured cooling kits with 7 up to 70 kW cooling capacity including a variety of different sorption chillers (absorption LiBr, absorption NH_3, adsorption silica gel, adsorption zeolith).

For direct comparison with compression technology, the $COP_{con\ el}$ for each cooling kit was calculated, illustrating the advantage of these products against traditional technology to substitute. Comparing the coefficient of performance from a compression chiller ($COP_{con\ el\ Airwell}$ = 4.63) with the equivalent $COP_{con\ el}$ of a sorption cooling kit ($COP_{con\ el\ Sys\ WFC18}$ = 10.93), illustrates the 2-3 times higher efficiency of sorption technology. In addition to primary energy savings and a lower emission of CDE (Carbon Dioxide Equivalent), the generation of a cooling capacity with a very low ratio of electricity for driving the machine is valued.

This fact will help to establish sorption technology for a sustainable energy supply even if electricity is renewably generated.

This research work led to competitive solar thermally driven sorption cooling systems, including specific engineering services for ensuring high efficient and reliable operation.

10.7 Limitations and future work

Within this research work the methodology for evaluating the SSE_{th} and the SSE_{th} was limited to solar thermally driven sorption systems. Future research work could apply the novel performance metrics to validate thermal systems with combinations of different heat sources as described in chapter 7. When validating a heat source combination, or heat sources other than a solar thermal system, the performance metrics could be named Storage Supply Efficiency or Supply Cooling Efficiency leading to the same abbreviations SSE_{th} and SCE_{th}. Furthermore, the novel performance metrics SSE_{th} and SCE_{th}, also have electrical equivalents – SSE_{el} and SCE_{el}, delivering the electric efficiency of the system. The newly defined metrics of this research ($SSE_{th,}$ SCE_{th} and COP_{con}) are intended to represent the first performance metrics of a metrics system which could be extended to include process metrics such as for heat generation or heat distribution, based on the methodology given in chapter 7. Furthermore, by including irreversible energy conversion, performance metrics such as the SSE_{con} and SCE_{con} can be derived.

10.8 Closing Statements

- This work has made an important contribution to the market entry of solar thermally driven cooling systems.
- The research has produced a novel methodology for systems engineering, leading to new methods and novel performance metrics, for investigating thermal energy systems.
- The defined performance metrics are simple to evaluate, concise and applicable to a variety of systems within the field, enabling an international accepted benchmarking of solar cooling systems.
- The holistic approach applied, delivered a generic design including thermodynamic optimization and market-readiness, representing a further step to a sustainable energy supply for the world's increasing heating and cooling demand.

11. References

Ayadi, O., Mauro, A., Aprile, M. & Motta, M. 2012, "Performance assessment for solar heating and cooling system for office building in Italy", *Energy Procedia,* vol. 30, no. 0, pp. 490-494.

Beccali, M., Cellura, M., Finocchiaro, P., Guarino, F., Longo, S. & Nocke, B. 2012, "Life Cycle Assessment Performance Comparison of Small Solar Thermal Cooling Systems with Conventional Plants Assisted with Photovoltaics", *Energy Procedia,* vol. 30, no. 0, pp. 893-903.

Becker, M., Helm, M. & Schweigler, C. 2009, *D-A2: Collection of selected systems schemes "Generic Systems", A technical report of subtask A (Pre-engineered systems for residential and small commercial applications)*, SHC IEA Task 38, Garching.

Bejan, A. 1996, *Entropy generation minimization : the method of thermodynamic optimization of finite-size systems and finite-time processes,* CRC Press, Boca Raton, Fla. ; London.

Butti, K., 1981. A golden thread : 2500 years of solar architecture and technology. London: Boyars.

Critoph, R.E. 2012, "Solid sorption cycles: A short history", *International Journal of Refrigeration,* vol. 35, no. 3, pp. 490-493.

Eicker, U. & Pietruschka, D. 2009, "Design and performance of solar powered absorption cooling systems in office buildings", *Energy and Buildings,* vol. 41, no. 1, pp. 81-91.

Eicker, U., Pietruschka, D. & Pesch, R. 2012, "Heat rejection and primary energy efficiency of solar driven absorption cooling systems", *International Journal of Refrigeration,* vol. 35, no. 3, pp. 729-738.

Einstein, A. & Seelig, C. 1959, *Mein Weltbild,* Neue, vom Verfasser duchges. und wesentlich erw. Aufl. edn, Ullstein, Frankfurt/M. [u.a.].

Gloy, K. 1996, *Die Geschichte des ganzheitlichen Denkens,* C.H. Beck, München.

Haberfellner, R. & Daenzer, W.F. 1994, *Systems engineering Methodik und Praxis,* 8. Aufl., neu bearb. und erg. edn, Verl. Industrielle Organisation, Zürich.

Hartmann, N., Glueck, C. & Schmidt, F.P. 2011, "Solar cooling for small office buildings: Comparison of solar thermal and photovoltaic options for two different European climates", *Renewable Energy [Renewable Energy].Vol.36,* vol. 36, no. 5, pp. 1329-1338.

Hastings, D. 2004, "The Future of Engineering Systems: Development of Engineering Leaders", *Engineering Systems Symposium*, MIT, , March 29-31, 2004.

Jaehnig, D. & Thuer, A. 2011, *D-A3b: Monitoring Results, A technical report of subtask A (Pre-engineered systems for residential and small commercial applications)*, IEA SHC Task 38, Gleisdorf.

Jakob, U. 2013, "Status and perspectives of solar cooling outside australia", *Australian Solar Cooling 2013 Conference,* ausSCIG, Sydney, April 12, 2013.

Jakob U. November 2011, "Overview market development and potential for solar cooling with focus on the Mediterranean area", *ESTEC 2011*.

Jakob, U. 2010, *Solar Cooling – Green Chiller Industry Association*, Proceedings of the Eurosun 2010, Graz, Austria.

Jakob, U. & De Montfort University. 2005, *Investigations into solar powered diffusion-absorption cooling machines*, De Montfort University.

Kaushik, S.C., Tomar, C.S. & Chandra, S. 1983, "Coefficient of performance of an ideal absorption cycle", *Applied Energy,* vol. 14, no. 2, pp. 115-121.

Kohlenbach, P. 2006, *Solar Cooling Systems with Absorption Chillers: Control Strategies and Transient Chiller Performance. PhD thesis*, Technical University of Berlin.

Koppelmann, U. 2001, *Produktmarketing Entscheidungsgrundlagen für Produktmanager,* 6, überarb u erw Aufl edn, , Berlin ; Heidelberg u.a.

Langniss, O., Seyboth, K., Beurskens, L. & Wakker, A. 2007, *Renewables for heating and cooling-untapped potential*, IEA, ECN Policy Studies, Paris, France.

Lavan, Z. and **Thompson**, J., 1977. Experimental study of thermally stratified hot water storage tanks. *Solar Energy,* **19**(5), pp. 519-524.

Marletta, L., Evola, G. & Sicurella, F. 2008, *Energy And Exergy Analysis Of Advanced Cycles For Solar Cooling*, Eurosun 2008, Lisbon, Portugal.

Martínez, P.J., Martínez, J.C. & Lucas, M. 2012, "Design and test results of a low-capacity solar cooling system in Alicante (Spain)", *Solar Energy,* vol. 86, no. 10, pp. 2950-2960.

Napolitano, A., Sparber, W., Thür, A., Finocchiaro, P. & Nocke, B. 2011, *Monitoring Procedure for Solar Cooling Systems, A joint technical report of subtask A and B (D-A3a / D-B3b)*, IEA SHC Task38, Bolzano.

Nowag, J., Boudéhenn, F., Le Denn, A., Lucas, F., Marc, O., Raduslescu, M. & Papillon, P. 2012, "Calculation of Performance Indicators for Solar Cooling, Heating and Domestic Hot Water Systems", *Energy Procedia,* vol. 30, no. 0, pp. 937-946.

Pahl, G. 2007, *Konstruktionslehre : Grundlagen erfolgreicher Produktentwicklung,* 7. Aufl. edn, Springer.

Peirce, C.S. 1974, *Collected papers of Charles Sanders Peirce : vol. 5 :Pragmatism and pragmaticism and vol. 6 :Scientific metaphysics,* Belknap Press of Harvard U.P.

Pietruschka, D., Jakob, U. & Eicker, U. 2010, "Solar Cooling for Southern Climates, Double Effect Absorption Chillers with High Concentrating Collectors Versus Standard Single Effect Systems", Graz, Austria, 28th September-1st October.

Pietruschka, D. & De Montfort University. 2010, *Model based control optimisation of renewable energy based HVAC Systems [electronic resource]*, De Montfort University.

Pons, M., Meunier, F., Cacciola, G., Critoph, R.E., Groll, M., Puigjaner, L., Spinner, B. & Ziegler, F. 1999, "Thermodynamic based comparison of sorption systems for cooling and heat pumping: Comparaison des performances thermodynamique des systèmes de pompes à chaleur à sorption dans des applications de refroidissement et de chauffage", *International Journal of Refrigeration,* vol. 22, no. 1, pp. 5-17.

Riechert, H.J. & Obert, P. 1991, *Rationelle Energieversorgung durch Kombination von Solaranlage und Block-Heizkraftwerk mit einem saisonalen Großwärmespeicher*, Steinbeis-Transferzentrum Energietechnik, Ulm, Germany.

Riepl, M., Loistl, F., Gurtner, R., Helm, M. & Schweigler, C. 2012, "Operational Performance Results of an Innovative Solar Thermal Cooling and Heating Plant", *Energy Procedia,* vol. 30, no. 0, pp. 974-985.

Safarik, M. 2003, *Solare Källteklimaerzeugung: Technologie, Erprobung, und Simulation*, Otto-von-Guericke-Universität Magdeburg.

Sparber, W., Napolitano, A., Eckert, G. & Preisler, A. 2009, "State of the art on existing solar heating and cooling systems", *IEA, Task38 Solar Air-Conditioningand Refrigeration,* .

Wasson, C.S. 2006, *System analysis, design, and development : concepts, principles, and practices,* Wiley-Interscience, Hoboken, N.J. ; Great Britain.

Wijeysundera, N.E. 1996, "Performance limits of absorption cycles with external heat-transfer irreversibilities", *Applied Thermal Engineering,* vol. 16, no. 2, pp. 175-181.

Wood, R.J., Al-Muslahi, S.M., O'Callaghan, P.W. and Probert, S.D., 1981. Thermally stratified hot water storage systems. *Applied Energy,* **9**(3), pp. 231-242.

Airwell Deutschland GmbH 2011, *Aqu@Logic Kaltwassersätze, Technische Beschreibung*, Frankfurt.

SolarNext AG 2010, *chillii© Preisliste 2010*, Rimsting.

Yazaki Europe Limited 2008, *WFC-SC5 Specifications*.