Schweizerische Eidgenossenschaft
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Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

Bundesamt für Energie BFE

Schlussbericht 31. October 2010

Low exergy building systems analysis: Integrated wastewater heat recovery and analysis of cooling systems with SEPE

Swiss contributions to IEA ECBCS Annex49 Low Exergy Systems for High Performance Buildings and Communities

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BFE-Vertrags- und Projektnummer: SI/500176-01 bzw. SI/500176

Contents

Abstract

It is imperative that global greenhouse gas emissions are reduced to avoid significant climate change, and the building sector is one of the largest single sources of emissions. The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems (ECBCS) Programme Annex 49, “Low Exergy Systems for High Performance Buildings and Communities,” provided the framework for an international collaboration to study ways to improve the built environment using the concept of exergy to maximize performance and minimize emissions. There were 12 countries participating. Switzerland contributed two primary projects: one implementing a new exergy analysis tool, and the other evaluating the exergetic potential of wastewater heat recovery.

The tool for exergy analysis, SEPE, was developed at KTH – The Royal Insitute of Technology, Stockholm, and tested and evaluated by Basler & Hofmann AG in Zurich. The tool is straightforward, Excel-based using the inbuilt iteration function for steady state calculations. It is presented with example analyses of three cooling systems. The second project was undertaken by the ETH Zurich Building Systems group. A series of models for decentralized heat recovery from wastewater are presented that evaluate the performance of an integrated low exergy system that exploits wastewater heat using a low temperature-lift, high COP heat pump. Along with the primary projects, the Swiss participation also provided several small contributions, which include tools and technologies for low exergy building systems. The outcome of the Annex 49 is in the form of an IT based guidebook including access to the tools developed. It is available at: http://www.annex49.com.

Zusammenfassung

Es ist zwingend notwendig, dass die globalen Treibhausgasemissionen reduziert werden, um einen signifikanten Klimawandel zu vermeiden. Die Bauwirtschaft ist eine der größten Quellen von Emissionen. Das International Energy Agency (IEA) lieferte mit dem Annex 49 “Low Exergy Systems for High Performance Buildings and Communities”, das Teil des Programms Energy Conservation in Buildings and Community Systems (ECBCS) ist, den Rahmen für eine internationale Zusammenarbeit. Ziel der Zusammenarbeit, an der 12 Länder beteiligt waren, war es zu untersuchen, wie der Gebäudebestand mit Hilfe des Exergie-Konzepts verbessert werden könnte, um dessen Leistung zu verbessern und gleichzeitg die Emissionen zu minimieren. Die Schweiz beteiligte sich mit zwei Projekten: zum Einen mit der Anwendung eines neuen Exergie-Analyse-Tools, zum Anderen mit der Untersuchung des exergetischen Potentials der Wärmerückgewinnung aus Abwasser.

Das Tool für die Exergieanalyse, SEPE, wurde an der KTH – The Royal Institute of Technology, Stockholm entwickelt und von der Basler & Hofmann AG getestet und bewertet. Das Tool basiert auf Excel und verwendet für den Aufbau eines Systems das copy-paste Prinzip. Die in Excel eingebaute Iterationsfunktion wird genutzt, um Steady-State-Berechnungen auszuführen. Das Tool wird anhand von Beispielrechnungen dreier Kühlsysteme präsentiert. Das zweite Projekt wurde von der ETH Zürich, Professur für Gebäudetechnik, durchgeführt. Eine Reihe von Modellen für die dezentrale Wärmerückgewinnung aus Abwasser wurden entwickelt, die die Leistung eines integrierten LowExergie-Systems, welches Wärme aus Abwasser mit Hilfe einer Wärmepumpe mit hohem COP und niedrigem Temperaturhub nutzt, bewertet. Neben diesen Projekten lieferte die Schweiz weitere kleinere Ergebnisse, wie potenzielle Methoden und Technologien für LowExergie-Gebäudetechnik. Die Ergebnisse des Annex 49 sind in Form eines IT-gestützten Handbuchs, das auch Zugang zu den Tools bietet, verfügbar. Es ist erhältlich unter: http://www.annex49.com.

1 Introduction:
IEA ECBCS Annex 49 Swiss Contributions

The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems (ECBCS) Annex 49, “Low Exergy Systems for High Performance Buildings and Communitiess,” provided the framework for an international collaboration to study ways to improve the built environment using the concept of exergy [1]. The participants came from 12 different countries (Austria • Canada • Denmark • Finland • Germany • Italy • Japan • Poland • Sweden • Switzerland • The Netherlands • USA). The Swiss participation by the ETH Zurich and Basler and Hofmann was supported by the Swiss Federal Office of Energy (SFOE) Energy in buildings research program.

1.1 Annex 49 Overview

1.1.1 Structure

The Annex 49 project aims to develop concepts that reduce the exergy demand of the built environment. A framework is setup to facilitate the transfer of ideas and further the development of low exergy systems and methods that will move toward this goal, which includes meetings, workshops, and conferences as well as newsletters, analysis tools, and working reports. The official working timeframe for the project was for 3 years, from approximately November 2006 to December 2009. There were two official “expert meetings” per year during the working phase taking place in various participant countries. There were several workshops held in conjunction with international conferences such as REHVA Clima 2007 and 2010. Also, two conferences were organized as a part of the Annex 49, one in April, 2009 in Heerlen, NL: “The Future of Sustainable Built Environments – Integrating the LowEx Approach,”” and then following the conclusion the working phase in Oct 2010, a final conference in Munich, DE: “The Future for Sustainable Built Environments with High Performance Building Systems.” There is also a “LowEx Building Symposium” planned for Zurich on 26.Nov, 2010 to disseminate some of the work done relating to the Swiss participation.

The Annex is lead by an Operating Agent and is split into four subtasks lead by different countries. Dietrich Schmidt from the Frauenhofer Institute for Building Physics in Germany was the Operating Agent. Subtask A on methodologies was lead by Finland. Subtask B on communities was lead by The Netherlands. Subtask C on technologies was lead by Sweden. Subtask D managed the results and dissemination and was managed by the Operating Agent in Germany.

The Swiss participation was lead by Forrest Meggers, researcher for Prof. Dr. Hansjürg Leibundgut, head of the Building Systems group in the Institute for Technology in Architecture at the ETH Zurich Faculty of Architecture. He, along with colleagues at the ETH Zurich focused on technologies for Subtask C. Petra Benz-Karlström of Basler and Hofmann in Zurich contributed a new exergy analysis tool as a part of Subtask A. The participation in the Annex requires a minimum effort of a total of 12 person-months per country. The Swiss participation, which amounted to about 17 person-months, was funded by the SFOE beginning in 2007 through the end of the Annex activities in November 2010.

1.1.2 Research

The building sector has a large environmental impact. One of the largest impacts comes from its greenhouse gas emissions. These are both indirect emissions from material inputs, construction, and waste, as well as direct emissions from operations. The most significant impact is from the CO_2 emissions caused by the energy demand for building operation. The improvement of building performance through new systems and better building and community design will lead to large reductions in these emissions. Therefore research and development in the area of building performance is essential to move toward a more sustainable society.

One of the areas of research that has the potential to improve the building performance is the concept of exergy applied to building systems and design. Exergy is a concept that comes from the second law of thermodynamics. It utilizes concepts within the second law of thermodynamics to better describe the true potential of an energy source. Instead of just describing an amount of raw energy, exergy describes the potential of that raw energy to perform useful work. Not all energy sources can have all their energy extracted for some purpose. Some systems, especially thermal systems, have physical limits described by the Second Law that prevent them from being 100% utilized. Therefore energy stored as heat may have a fixed amount of energy described by its heat capacity and mass, but in reality only a portion of that energy can be extracted using a thermodynamic cycle to perform work (i.e. produce electricity or run a motor). This true potential is captured by the concept of exergy.

A good example to consider is the comparison of energy to exergy for common items. An ideal battery contains 100 kJ of energy and an ideally insulated pot at 40°C in a 20°C room with a volume of 1.2 L has the same amount of energy based on its heat capacity and mass. But the battery can provide exactly 100 kJ of work or exergy, while the water can only have a maximum of 7 kJ of work or exergy available. A reverse example would be to consider two coffees: one cup of 300 mL, 40 °C American coffee and one cup of 30 mL, 95°C Italian espresso. Compared to the 20 °C room, the big American coffee has 25 kJ of energy and the little Italian espresso has only 9 kJ of energy. If we use electric resistance heaters to heat these coffees we have to use exactly that amount of electricity (electricity= 100% exergy). But if we use the thermodynamic cycle of heat pump to move heat from the 20 °C environment into the coffees, the true exergetic value is revealed. The actual exergy of the American coffee is only 0.8 kJ while the Italian espresso is larger at 1 kJ. Therefore with an ideal heat pump the lower temperature, larger mass system, can be heated with less exergy demand, and this is analogous to building systems.

Buildings are just large thermal systems, and thus the concept of exergy can be used to better optimize these systems. A system at a higher temperature has more potential, and thus higher exergy demand. By using exergy analysis this demand can be reduced and minimized throughout the chain of building systems: from supply to distribution to emission to the space demand. Exergy analysis helps to design systems that not only minimize energy or heat losses, but also reduces losses in potential as described by the exergy in high temperature systems. Therefore, temperature gradients are minimized, and rooms are, for example in an ideal case, heated with low temperature heating systems and high temperature cooling systems. Exergy analysis also helps to identify sources of irreversibilities in building systems that may be causing losses not obvious in an energy analysis alone. These could be from a improperly sized system whose components are not properly matched and through exergy analysis can be improved for both optimal performance as well as cost effectiveness.

The scope of the research for Annex 49 is to evaluate the potential for further application of low exergy technologies, which began with another IEA ECBCS Annex 37, as well as to extend that evaluation into the broader community sector as well. The use of high quality, high temperature, and thus inefficient exergy supply systems in buildings and communities should be minimized. This means taking a closer look at how combustion systems are implemented and more importantly, evaluated in the building sector, because a low exergy philosophy often provides a more effective solution, both in terms of environmental impact and emissions, as well as economically.

The objectives within the Annex follow along the streams of the four subtask and include analysis of specific building and community systems, as well as the development and expansion of tools for applying exergy analysis to the built environment. The research should provide analysis of all building types from residential to commercial to industrial, and further include consideration on how they can be combined in community systems to optimize performance. The overall objective is thus to pinpoint ways to reduce the exergy demand of the building sector and thereby reduce the CO_2 emissions and increase the sustainability of the building stock. The result should be the dissemination of this information through the Annex outcomes.

1.1.3 Outcomes

The core outcome of the Annex is a sharing of information and research between a large international group. This is achieved through the expert meetings, and collaboration on a variety of projects and events.

A broader outcome is the dissemination of information through the conferences and workshops organized by the Annex. These provide an opportunity to demonstrate the benefits and potential of implementing low exergy systems in high performance building and community systems, while also encouraging basic improvements to common design practices and methods. This influence is achieved on global scale through the international participation.

The principal outcome of the Annex will be the final report and guidebook that will serve as a permanent dissemination source for the work done by the group. This will include online access (www.annex49.com) that includes links to all the tools developed during the Annex as well as results of case studies and system evaluations performed as a part of the project. The expansion and further development of how exergy can be applied to the building sector will also be explained in the guidebook, providing a more common ground for how systems and buildings can be evaluated and improved using exergy analysis.

1.2 Subtasks

The Annex was divided into four subtasks as described in [1]:

1.2.1 Subtask A: Exergy Analyses Methodologies.

Objective

Development, assessment and analysis of methodologies, including tools for design and performance analysis of community systems and buildings.

Main work items:

- Exergy flow analyses of complex systems for thermodynamic performance and sustainability evaluation.
- New dynamic exergy analysis methods accounting for changing ambient conditions.
- System optimisation strategies.
- Procedures, models and software tools for design and performance analyses.
- Life cycle economical impacts of LowEx design rules.

Subtask A provides the necessary framework for more detailed exergy analyses applied to the community level and to buildings. Models and software for design and performance evaluation, in particular for the combined exergy/energy analysis, are produced and published. Based on the conducted analyses, pre-normative work has been conducted.

1.2.2 Subtask B: Exergy efficient community supply systems.

Objective

Development of exergy concepts, distribution, generation, and storage systems that meet all exergy demands of community members with a minimum input of primary energy.

Main work items:

- Innovative technologies for energy supply structures at different exergy levels.
- Innovative technologies for the local utilization of renewable and ambient resources, e.g. heat pumps.
- Advanced system concepts and solutions for the distribution, local generation and storage of energy/exergy.

The design of low exergy systems has to be performed at the community level, taking the concerns of building stock owners into consideration. For example, district heating can be a very powerful low exergy concept if many buildings are connected to the expensive distribution systems. An advanced building design can lead to lower district heating operating temperatures, thus increasing the power plant efficiency.

1.2.3 Subtask C: Exergy efficient building technologies.

Objective

This subtask is focused on the reduction of exergy demand for heating, cooling and ventilating buildings. The work includes the development of best-practice guidelines for implementing innovative building technology solutions and for establishing a holistic system approach to the exergy assessment of buildings.

Main work items:

- Innovative technologies for low exergy heating and cooling.
- Innovative control concepts and strategies for a demand controlled exergy supply.
- System concepts and solutions, including innovative exergy storage systems.
- Exergy as an innovation driver in buildings and building service systems.

The core issues in Subtask C are the development and analyses of innovative techniques. Exergy could become an innovation driver for building systems. On the one hand, improvement potential and technological breakthrough needs have been addressed. While, on the other hand, system engineering and analysis have been examined. Advanced modelling and implementation of combined dynamic exergy and energy analyses show the potential of new technologies. Furthermore, investigations of storage systems provide an optimized implementation strategy.

1.2.4 Subtask D: Knowledge transfer, dissemination

Objective

This subtask focuses on the collection and spread of information on ongoing and finished work. This includes the set-up of information platforms and the organisation of seminars and workshops.

Main work items:

- Initiation of demonstration projects and development of new activity formats between research and business.
- Documentation of best practice examples.

- Newsletters, website and seminars/workshops.
- Design guide.

The results of Subtasks A, B and C are provided as input to the joint activity in Subtask D. A web-based information platform, open seminars and widespread scientific publications are used for the dissemination of information. It is planned to condense the topics of the annex in order to reach a public level.

1.3 Swiss Contributions

The principle contributions from Switzerland to the Annex 49 were in the form of analysis tools and low exergy systems analysis. The two primary projects was to create new tool, called SEPE, to do exergy analysis for buildings, and to analyze the potential of a low exergy system to recovery heat from wastewater. Both are included in the Final Report [1].

1.3.1 Contribution to Subtask A: SEPE

Within the context of Annex 49, the SEPE project was a collaboration between Petra Karlström of Balser and Hofmann, Gudni Johanneson and Marco Molinari of KTH University in Sweden. The work fell under contributions to the Subtask A for providing new tools and methodologies and is presented in Chapter 2.

1.3.2 Contribution to Subtask C: Wastewater heat recovery

The wastewater heat recovery project fell under Subtask C in the Annex 49 as the development and analysis of a new technology. The analysis was done within the ETH Zurich Building Systems group and was presented at several conferences and meetings during the course of the Annex, and was a part of the 4th Newsletter and Midterm Report. It is presented in Chapter 3.

1.3.3 Other Contributions

In the course of the Annex related work being carried out by the Swiss participants also provided small additions to the overall Annex outcome. These included some tools being developed in Zurich as well as some other new technologies that were discussed within the Annex framework. Other members of the Building Systems group at the ETH also contributed presentations at the Annex conferences and workshops. Some of these concepts were incorporated into the publications of the Annex and the final report and they are presented in Chapter 4.

2 Contribution to Subtask A: Exergy analysis of cooling systems using SEPE

2.1 Introduction and Motivation for SEPE

Ventilation and cooling of buildings constitute a constantly increasing part of Switzerland's total energy consumption. If we continue with business as usual, the consumption will increase to 2.9 TWh/a in the year 2035. One of the reasons for the augmentation in energy consumption, are increasing user demands. In combination with increasing ambient air temperatures, cooling of buildings will become a necessity. To minimise costs and energy demand, available cooling solutions must be optimised and innovative approaches encouraged.

The growing awareness of climate change and its implications in combination with rising prices on fossil fuels have boosted the demand for energy efficient, even plus-energy buildings. By minimising the losses of energy used for conditioning the indoor environment, heating and cooling systems with a low temperature difference to the room can be used. Floor heating or cooling is a common example. Using close to room temperatures opens the possibility to utilise low quality energy sources, for instance cooling with ambient heat sinks or waste energy.

The change to renewable energy sources reduces the environmental impact caused by room conditioning. A further approach is to optimise the HVAC systems themselves. The performance of HVAC systems is usually evaluated based on the first law of thermodynamics. However, compared to energy analysis, the exergy analysis (second law of thermodynamics) can better and more accurately show the location of inefficiencies, see for instance [2]. The results from exergy analysis can be used to assess and optimise the performance of HVAC systems. The combination of energy and exergy analysis can present a whole picture of the system performance.

This work was done in close cooperation with Tech. Lic. Marco Molinari and affiliated Prof. Gudni Johannesson at the Division of building technology, School of architecture and the built environment at KTH – The Royal Institute of Technology, Stockholm.

2.2 The concept of exergy

In everyday language as well as in the technical discussion it is claimed that energy is consumed ("energy consumption" etc.). This use of language is in fact in contradiction to the first law of thermodynamics which states that the total amount of energy is conserved, though the forms of energy may change. What is meant with "energy consumption" is instead the conversion of high quality energy into low quality energy. The exergy content expresses the quality of an energy source or flow.

Again, to illustrate the difference between energy and exergy: it is obvious that 100 kJ of electrical energy stored in a 12 V / 2,3 Ah car battery is easier to transform into something useful for us, than the same amount of 100 kJ thermal energy stored in 1 kg of water at a temperature of 43°C. With the electricity a machine can be run, or a light bulb of 40 W for 42 min. 1 kg of water at 43°C can be used to wash hands or washing the dishes [3]. The *energy* content is the same for the battery and the water, while the *exergy* content in the battery is considerably higher.

Traditionally exergy analysis has been used in mechanical engineering including power plant design and optimisation. Whereas the exergy optimisation of a power plant aims at increasing the power output, exergy optimisation in buildings aim to decrease the exergy input [4].

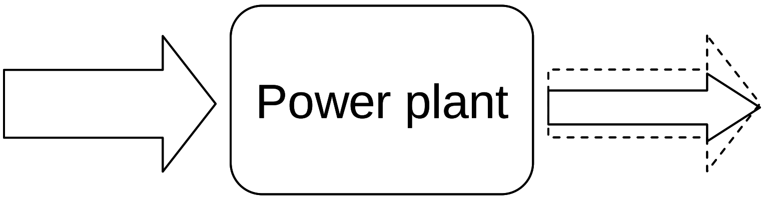

Figure 1: Power plant optimisation aims at increasing the power output. [4]

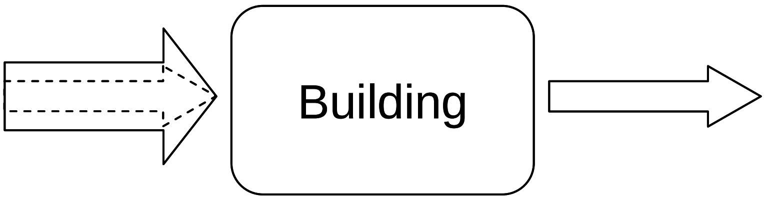

Figure 2: Building exergy optimisation aims at decreasing the power input. [4]

The exergy content is calculated in relation to a reference state. Different applications use different reference states. For calculations concerning the built environment, the ambient conditions, such as dry-bulb outdoor temperature and outdoor pressure, are the most common.

2.3 The tool

The SEPE – Software for Exergy Performance Assessment is a tool developed at the Division of Building Technology at KTH, based on previous work [5], to evaluate HVAC systems consisting of a chain of components. It is not a tool for optimising a single component, for instance a heat pump. A system evaluation with SEPE can be used to compare different system set-ups in a first stage of planning. The tool is Excel-based and uses iterative steady state calculations. The programme can be downloaded at http://www.annex49.com

2.3.1 Programme setup

SEPE is a straightforward, modular Excel calculation sheet. It consists of *components* which can freely be combined to represent a mass and heat transfer system. The reference conditions can be chosen freely, however it is recommended to use the outdoor conditions.

The following components are available:

Generation	**Distribution**	**Emission**	**Other**
boiler (oil, LNG, el.)	air duct	air handling unit	heat exchanger (counter or parallell flow)
heat pump	water pipe	floor cooling / heating	room model

thermal solar collector	pump	radiator
chiller	fan	
adiabatic saturator		

Tab. 1: Available components in SEPE at the time of writing

Each component consists of three parts: Input values, characteristic equations and output values, see Figure 3.

Fan					
	IN par	Env pressure [Pa]		OUT par	
	Pressure [Pa]	Env temp [K]		Pressure [Pa]	
	Temperature [C]	Medium		Temperature [C]	
input values	Temperature [K]	Mass flow [kg/s]	**characteristic equations**	Temperature [K]	**output values**
	Ex ch,s [J/kg]	Power input [W]		Ex ch,s [J/kg]	
	Ex ph,s [J/kg]	Pressure rise [Pa]		Ex ph,s [J/kg]	
	Ex th,s [J/kg]	Exergy ph rise [W]		Ex th,s [J/kg]	
	Ex total,s [J/kg]			Ex total,s [J/kg]	
	RH [%]			RH [%]	
	x [kgw/kga]	Exergy efficiency [%]		x [kgw/kga]	
	Exergy total [W]	**Exergy loss [W]**		Exergy total [W]	

Figure 3: Example of a component, fan

Components with two medium flows, for instance the heat exchanger, have a different setup, Figure 4

	Parallel-flow		Heat exchanger		Water to Water	1000
		IN par	Env pressure [Pa]		OUT par	
		Pressure [Pa]	Env temp [K]		Pressure [Pa]	
		Temperature [C]	Medium		Temperature [C]	
primary side	**input values**	Temperature [K]	Mass flow [kg/s]	**characteristic equations**	Temperature [K]	**output values**
		Ex ch,s [J/kg]	Pressure loss [Pa]		Ex ch,s [J/kg]	
		Ex ph,s [J/kg]	Heat flow [W]		Ex ph,s [J/kg]	
		Ex th,s [J/kg]	**Effectiveness**		Ex th,s [J/kg]	
		Ex total,s [J/kg]	Delta T [K]		Ex total,s [J/kg]	
		RH [%]	Exergy drop [W]		RH [%]	
		x [kgw/kga]			x [kgw/kga]	
		Exergy total [W]	Cp [J/kgK]		Exergy total [W]	
		C ratio [-]	Thermal efficiency		Thermal exergy efficiency	
		Area [m2]			NTU	
		Cmax [J/K]			C1 [J/K]	
		Cmin [J/K]	**Exergy loss [W]**		C2 [J/K]	
		IN par	Env pressure [Pa]		OUT par	
		Pressure [Pa]	Env temp [K]		Pressure [Pa]	
		Temperature [C]	Medium		Temperature [C]	
secondary side	**input values**	Temperature [K]	Mass flow [kg/s]	**characteristic equations**	Temperature [K]	**output values**
		Ex ch,s [J/kg]	Pressure loss [Pa]		Ex ch,s [J/kg]	
		Ex ph,s [J/kg]	Heat flow [W]		Ex ph,s [J/kg]	
		Ex th,s [J/kg]	Delta T [K]		Ex th,s [J/kg]	
		Ex total,s [J/kg]	Exergy rise [W]		Ex total,s [J/kg]	
		RH [%]			RH [%]	
		x [kgw/kga]			x [kgw/kga]	
		Exergy total [W]	Cp [J/kgK]		Exergy total [W]	

Figure 4 Example of a two medium component, heat exchanger

The system to be calculated is assembled by copy-pasting the different components in correct order and connecting the controlling variables pressure, absolute temperature and in case of air as medium, the humidity ratio. Further parameters such as medium type, heat exchanger area etc. are inserted in the respective components. The result is iterated with Excel's inbuilt iteration option. Figure 5 shows the interface of an example system setup. Air or water can be used as energy carrying medium.

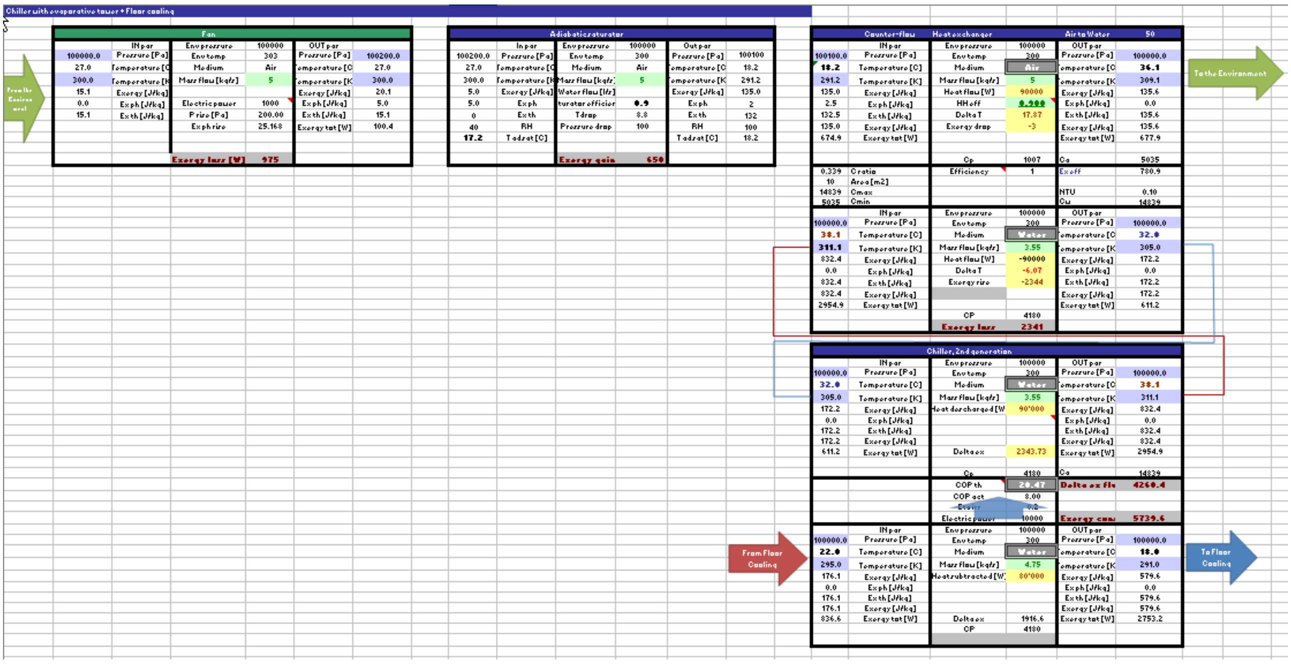

Figure 5: Example of a system setup

2.3.2 Calculation method

The following equations are used for calculating the exergy content of the medium, [6-8]

(1) $$Ex = Ex_{ph} + Ex_{ch}$$

Water:

(2) $$Ex_{ph} = c_p\left[(T - T_0) - T_0 \ln\frac{T}{T_0}\right] + v_m(P - P_0)$$

(3) $$Ex_{th} = c_p\left[(T - T_0) - T_0 \ln\frac{T}{T_0}\right]$$

(4) $$Ex_{pr} = \upsilon_m(P - P_0)$$

Air, assuming ideal gas behaviour:

(5) $$Ex_{ph} = c_p(T - T_0) - T_0\left[c_p \ln\frac{T}{T_0} - R\ln\frac{P}{P_0}\right]$$

(6) $$Ex_{th} = c_p \left[(T - T_0) - T \ln \frac{T}{T_0} \right]$$

(7) $$Ex_{pr} = T_0 R \ln \frac{P}{P_0}$$

(8) $$Ex_{ch} = h_f(T) - h_g(T_0) - T_0 \cdot s_f(T) + T_0 \cdot s_g(T_0) + \left[P - P_{sat}(T) \right] \cdot v_f(T) - R_v \cdot T_0 \cdot \ln \varphi_0$$

E_{ph} is the physical exergy including E_{th}, the thermal component and E_{pr}, the pressure component, [J/kg]. E_{ch} is the chemical exergy, [J/kg], relevant for the exergy content of the air. c is the specific heat (constant), [J/(kgK)], T is the medium temperature, [K], T_0 the reference temperature, [K], ν_m the specific volume of the medium, [m^3/kg], determined at the temperature T_0. P is the medium pressure, [Pa], P_0 is the reference pressure, [Pa], c_p is the specific heat at constant pressure, [J/(kgK)] and R the specific ideal gas constant [(J/(kgK)]. h_f is the specific enthalpy for saturated liquid [J/kg], h_g is the specific enthalpy for the air [J/kg], s_f is the specific entropy for the air [J/(kgK)], s_g is the specific entropy for the air [J/(kgK)], P_{sat} is the pressure for saturated liquid, [Pa]. v_f is the specific volume for saturated liquid, R_v is the specific ideal gas constant for water vapour and finally φ_0 is the reference relative humidity.

By multiplying the specific exergy by the mass flow in the components, the exergy flows are obtained for each system node.

The chemical exergy component for air considers the exergy available in water vapour. As shown in [8-10], exergy calculations for cooling cases can lead to inaccurate results if only dry air is considered.

2.4 Comparison of three cooling systems with SEPE

Three different cooling system setups were evaluated with SEPE. The building was modelled with the following boundary conditions:

	Conditioned floor area	**Wall**	**Windows**
Area [m^2]	1200	500	250
U-Values [W/m^{2}K]	-	0.15	1.0

Tab. 2: Simulated building, geometry:

Internal loads [W/m^2]	**External loads** [W/m^2]	**Set point temperature room** [°C]	**Delivered cooling power** [W/m^2]
10	15	26	26

Tab. 3: Simulated building, heat loads, set point temperature and delivered cooling power

Temperature [°C]	**Pressure** [kPa]	**Relative humidity** [%]
30	110	40

Tab. 4: Reference conditions for the exergy analysis (environment conditions)

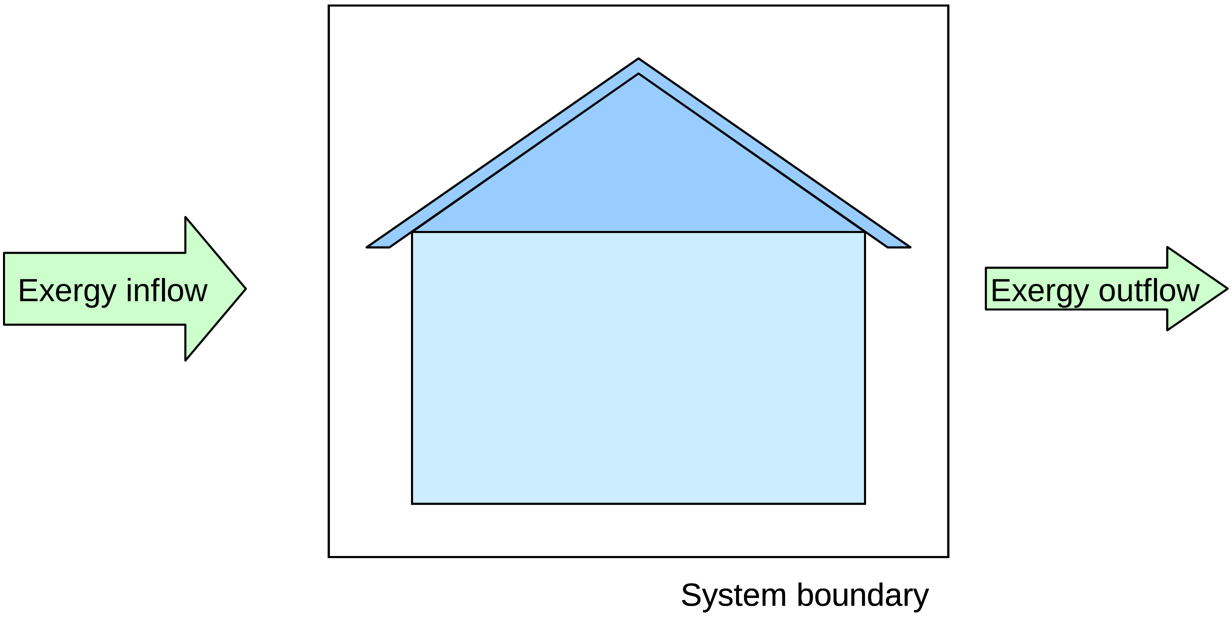

Figure 6: System boundary exergy flow

Two of the systems use water as cold carrying medium, in the third case air cooling is used. The calculated examples can be found together with the tool at http://www.annex49.com.

2.4.1 System 1: Chiller with high temperature lift, hybrid cooling tower and floor cooling

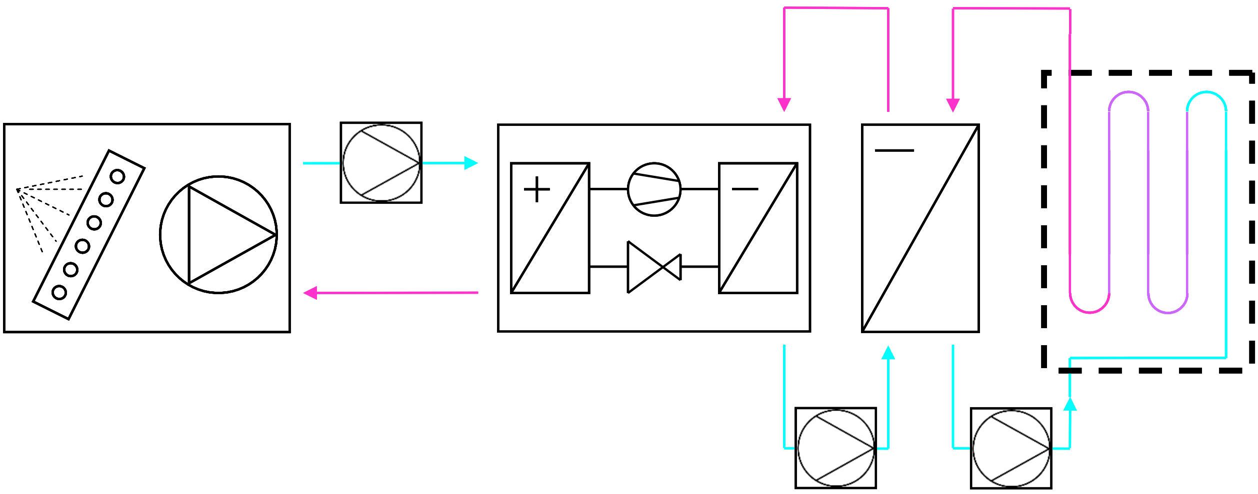

Figure 7: Configuration System 1

System 1's generation system consists of a chiller with a COP of 4, a hybrid cooling tower and a heat exchanger. The heat exchanger is necessary since the chiller produces cold water with a temperature of 11°C. This temperature is too low to be sent directly to the emission system, floor cooling. The inlet temperature to the floor cooling is 18°C. The return temperature from the floor cooling is 22°C. The return temperature to the chiller from the heat exchanger is 15°C.

System 1 was assembled in SEPE according to Figure 8.

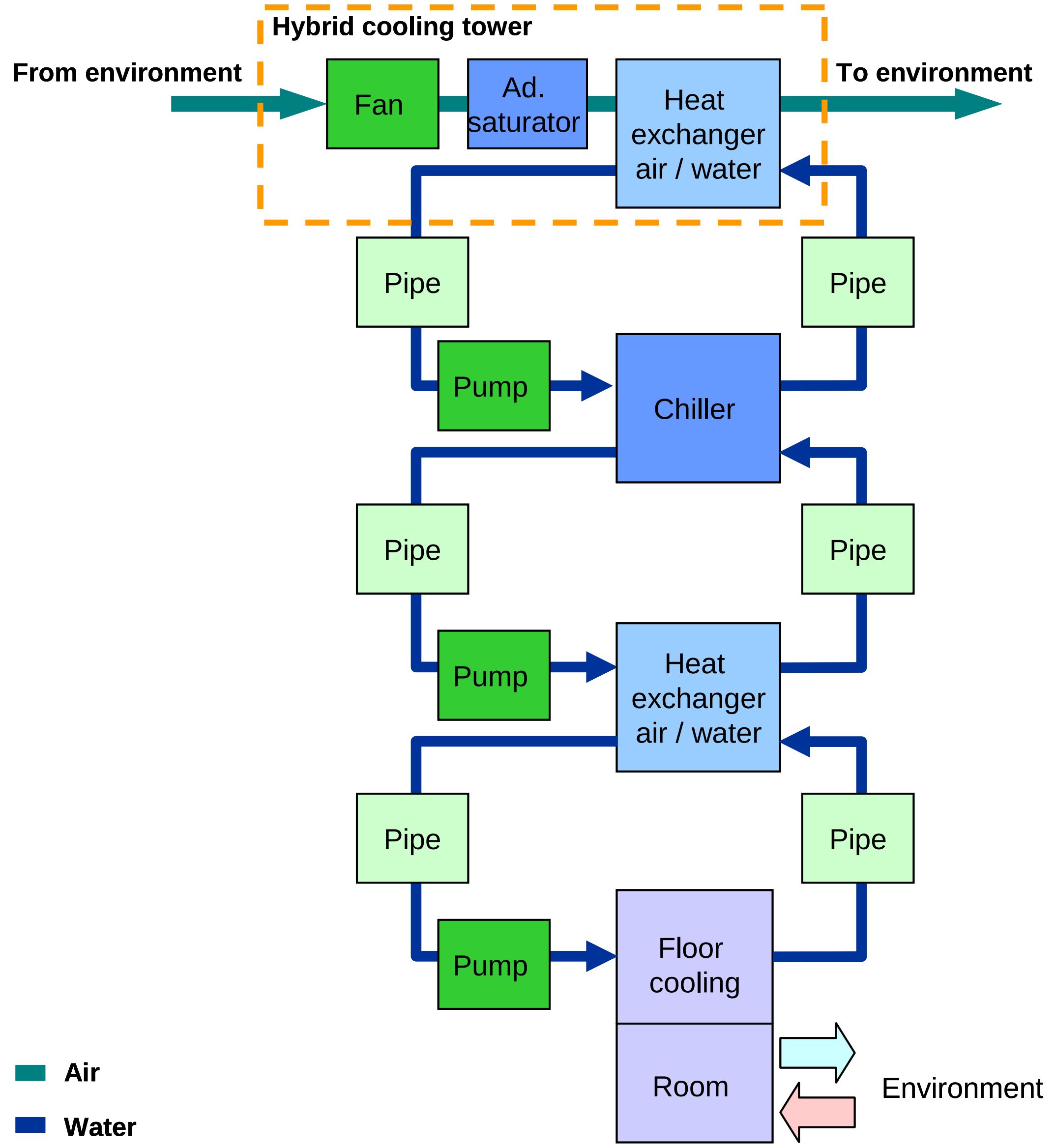

Figure 8: Representation of System 1 in SEPE

The input parameters for the different components can be found in Appendix 1.

Results

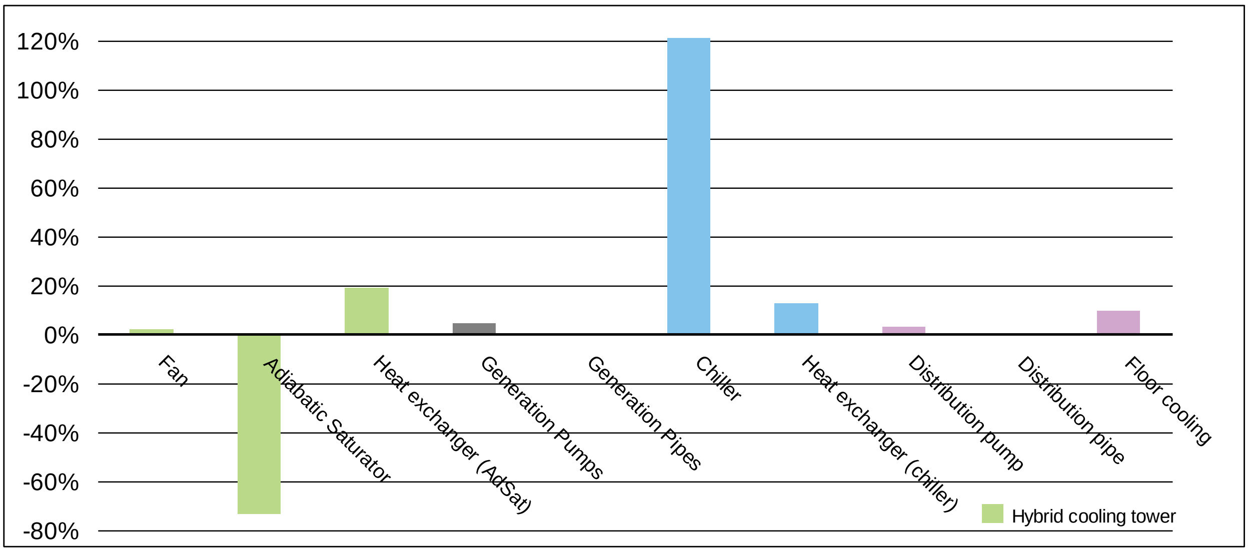

Figure 9: Exergy losses along the component chain for System 1

Exergy losses	Fan	Adiabatic Saturator	Heat exchanger (AdSat)	Generation Pumps	Generation Pipes	Chiller	Heat exchanger (chiller)	Distribution pump	Distribution pipe	Floor cooling	Total
[W]	100	-3570	920	210	9	5960	610	160	2	460	4860
	2%	-73%	19%	4%	0%	123%	13%	3%	0%	9%	100%

Tab. 5: Exergy losses in the component chain for System 1

According to Figure 9 and Tab. 5 it is obvious that the chiller causes the greatest exergy losses. The air to water heat exchanger in the hybrid cooling tower is responsible for 20% of the losses. The floor cooling exergy losses are due to the pressure losses in the component. Visible is as well that the exergy gained from the outside air by the adiabatic saturator make up for more than 50% of the losses in the chiller. The pump and pipe losses are small in comparison to the overall losses.

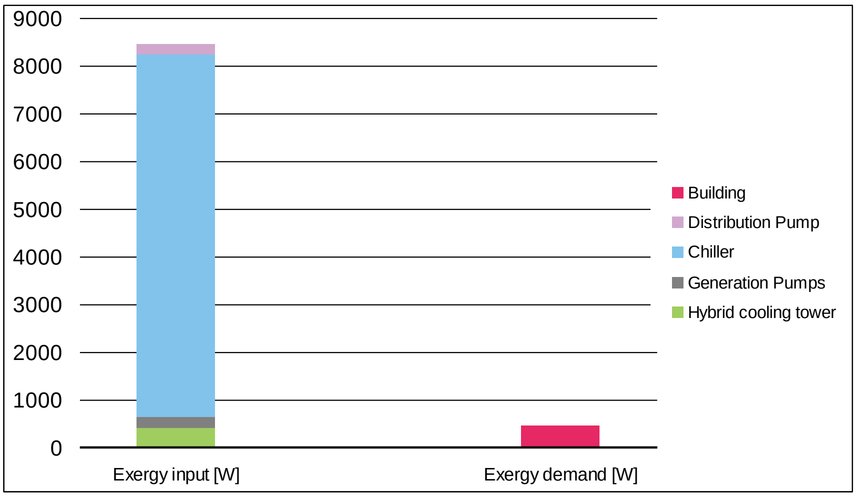

Figure 10: Exergy input and demand for System 1

	Hybrid cooling tower	Generation Pumps	Chiller	Distribution Pump	Building	Total
Exergy input [W]	400	250	7600	200		8450
	5%	3%	90%	2%		100%
Exergy demand [W]					460	460

Tab. 6: Exergy input and demand for System 1

In Figure 10 and Tab. 6 the exergy input vs. the exergy demand is shown. The resulting exergy efficiency is a mere 5%.

2.4.2 System 2: Chiller with low temperature lift, hybrid cooling tower and floor cooling

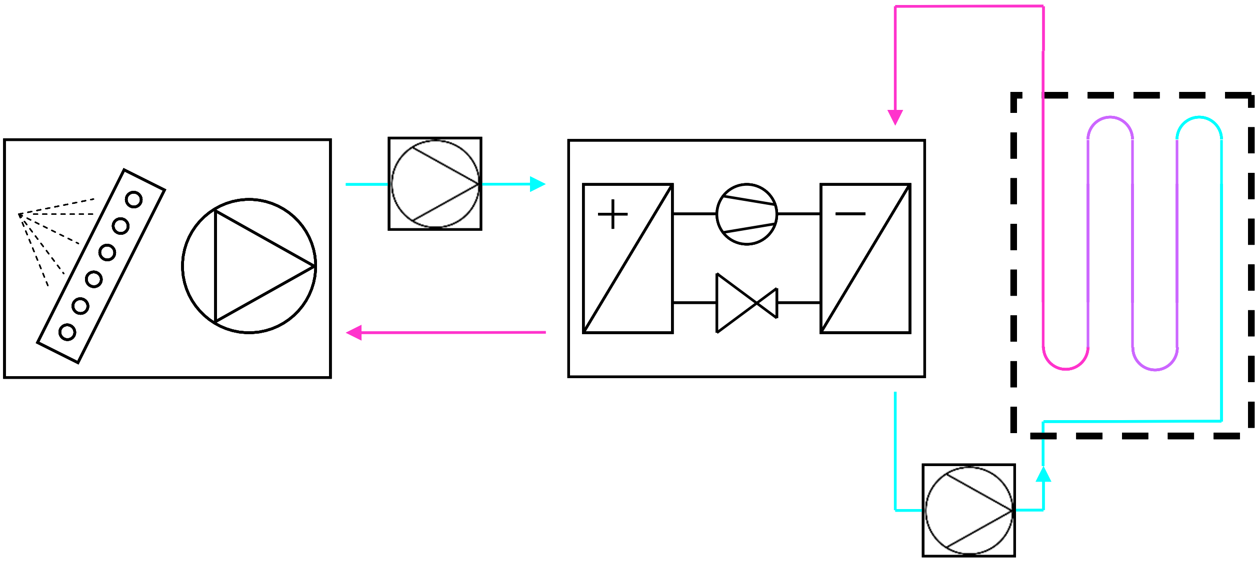

Figure 11: Configuration System 2

System 2's generation system consists of a chiller with a COP of 8 and a hybrid cooling tower. The chiller produces cold water of 18°C which can be distributed directly to the floor cooling. The return temperature from the floor cooling is 22°C.

System 2 was assembled in SEPE according to Figure 12.

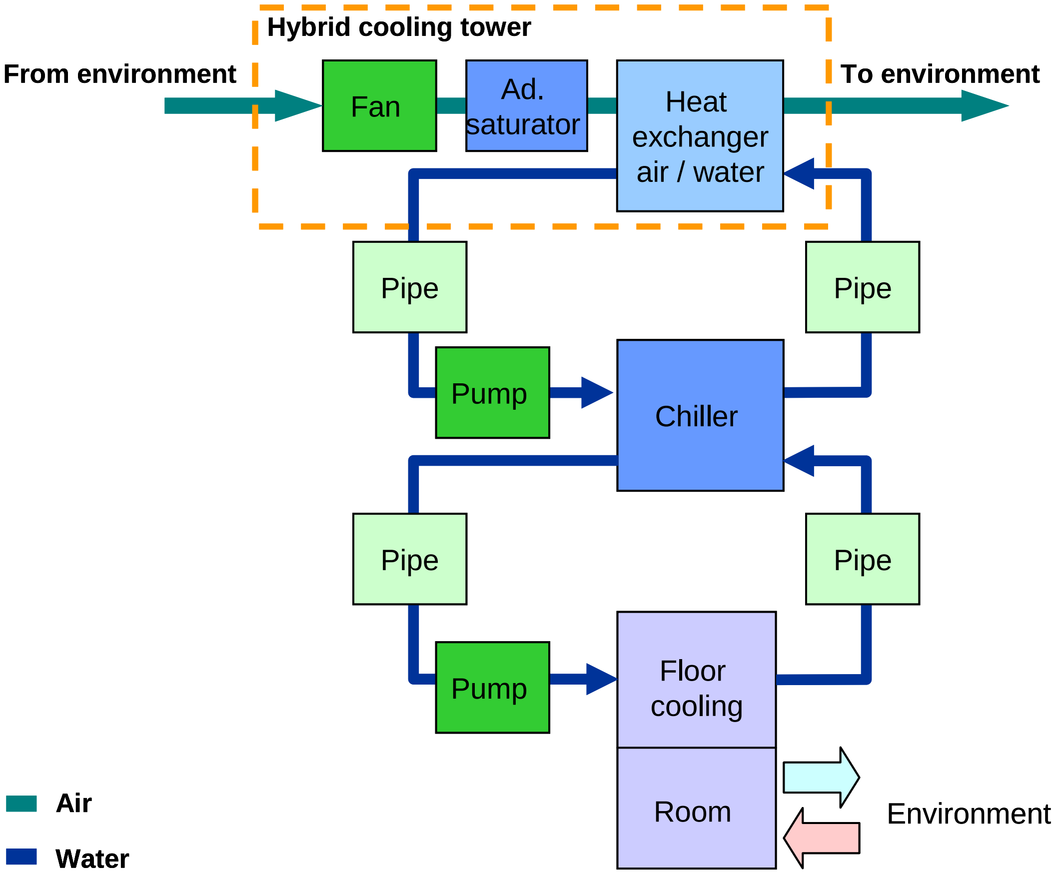

Figure 12: Representation of System 2 in SEPE

The input parameters for the different components can be found in Appendix 1.

Results

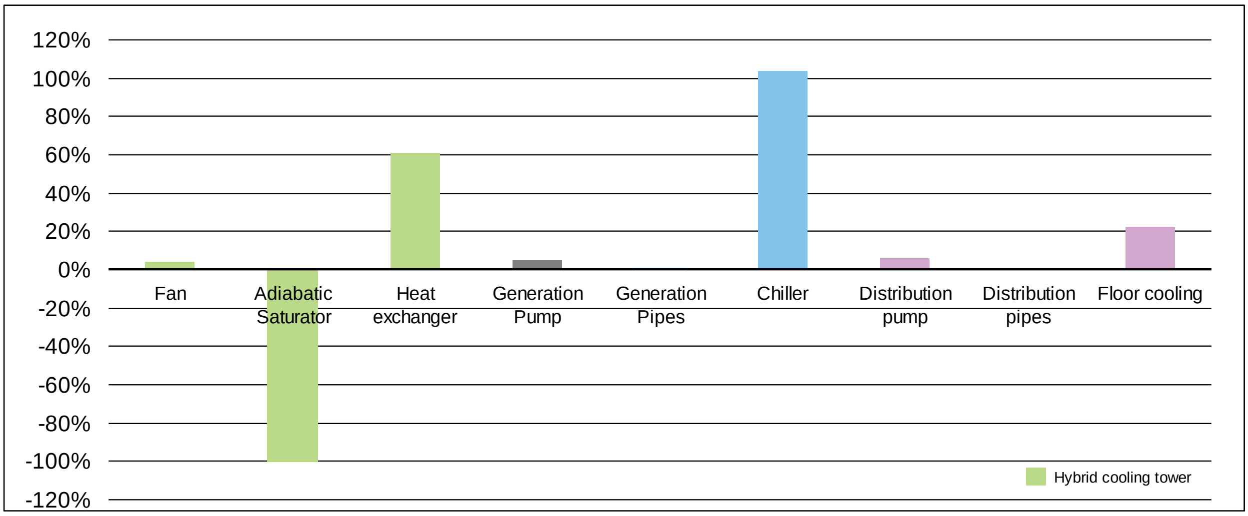

Figure 13: Exergy losses along the component chain for System 2

Exergy losses	Fan	Adiabatic Saturator	Heat exchanger	Generation Pump	Generation Pipes	Chiller	Distribution pump	Distribution pipes	Floor cooling	Total
[W]	100	-2800	1690	130	10	2880	150	4	610	2770
	4%	-101%	61%	5%	0%	104%	5%	0%	22%	

Tab. 7: Exergy losses in the component chain for System 2

According to Figure 13 and Tab. 7, here it is also clear that the chiller causes the greatest exergy losses. The air to water heat exchanger in the hybrid cooling tower is responsible for 60% of the losses. The floor cooling exergy losses are due to the pressure losses in the component, its contribution to the overall losses is relatively high. It is notable that in this case, the exergy gained from the outside air by the adiabatic saturator almost makes up for the total losses in the chiller. The pump and pipe losses are small in comparison to the overall losses.

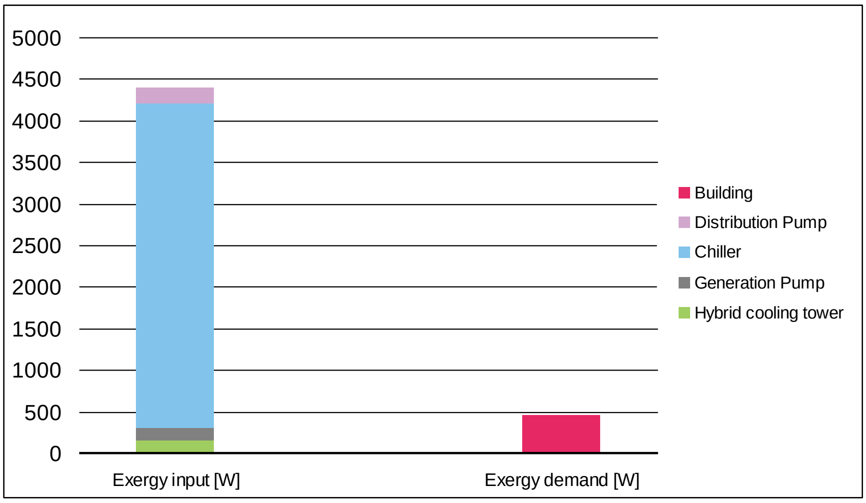

Figure 14: Exergy input and demand for System 2

	Hybrid cooling tower	Generation Pump	Chiller	Distribution Pump	Building	Total
Exergy input [W]	150	150	3900	200		4400
	3%	3%	89%	5%		100%
Exergy demand [W]					450	450

Tab. 8: Exergy input and demand for System 2

In Figure 14 and Tab. 8 the exergy input vs. the exergy demand is shown. The resulting exergy efficiency is 10%. This is a 100% performance increase compared to System 1.

2.4.3 System 3: Chiller with high temperature lift, hybrid cooling tower and air cooling

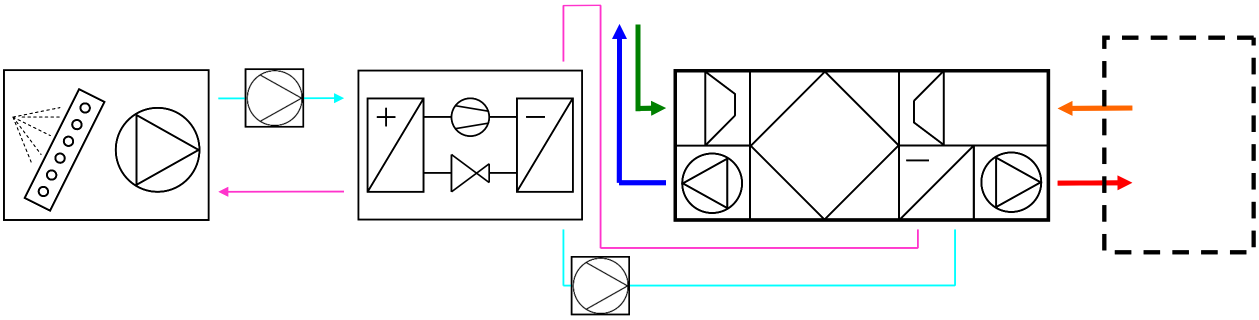

Figure 15: Configuration System 3

System 3's generation system consists of a chiller with a COP of 4, a hybrid cooling tower and an air handling unit. The building is conditioned with cool air, 10 $m^3/h, m^2$. The chiller produces cold water with a temperature of 9.5°C, the return temperature from the air handling unit is 18°C.

System 3 was assembled in SEPE according to Figure 16.

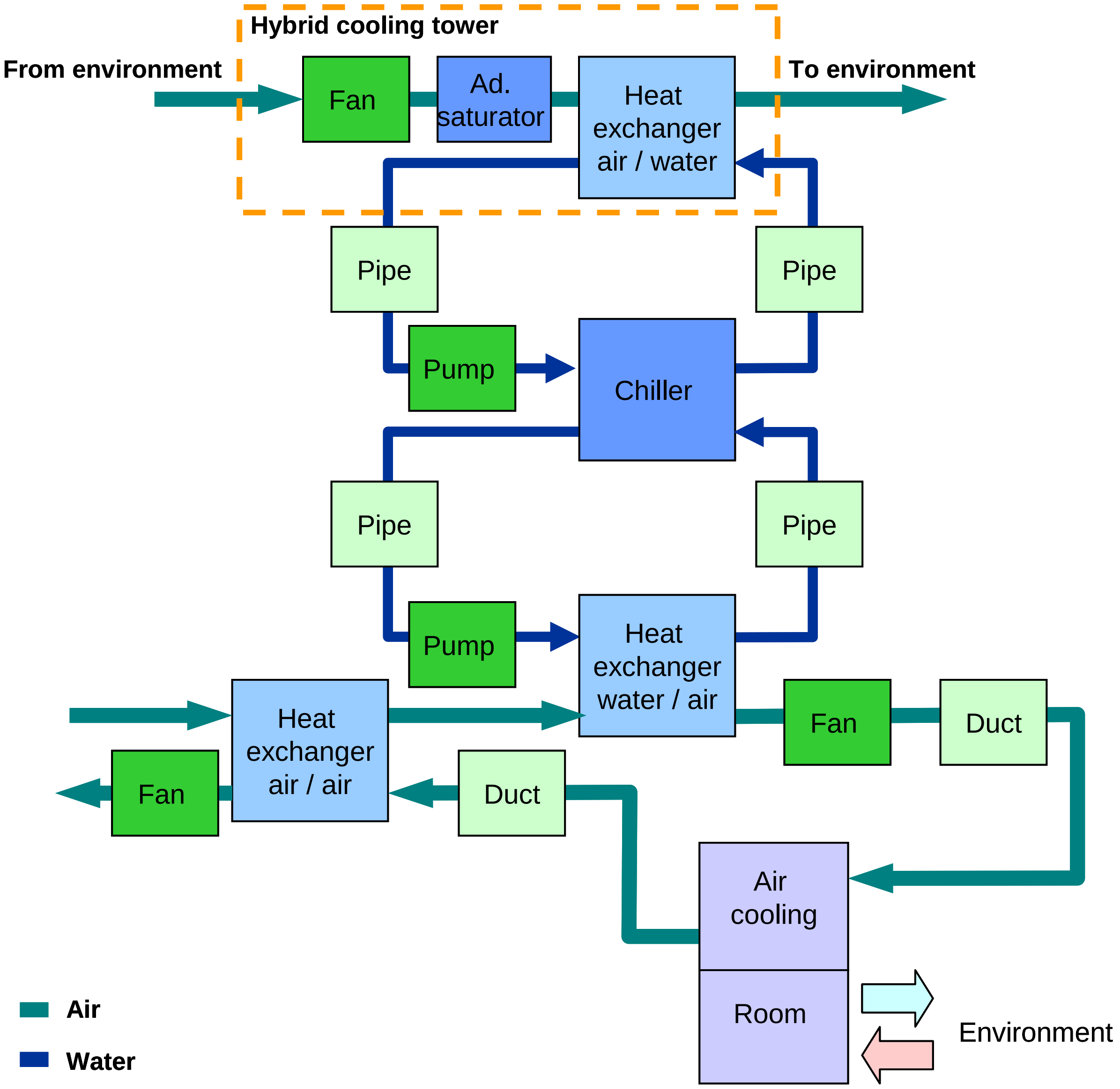

Figure 16: Representation of System 3 in SEPE

The input parameters for the different components can be found in Appendix 1.

Results

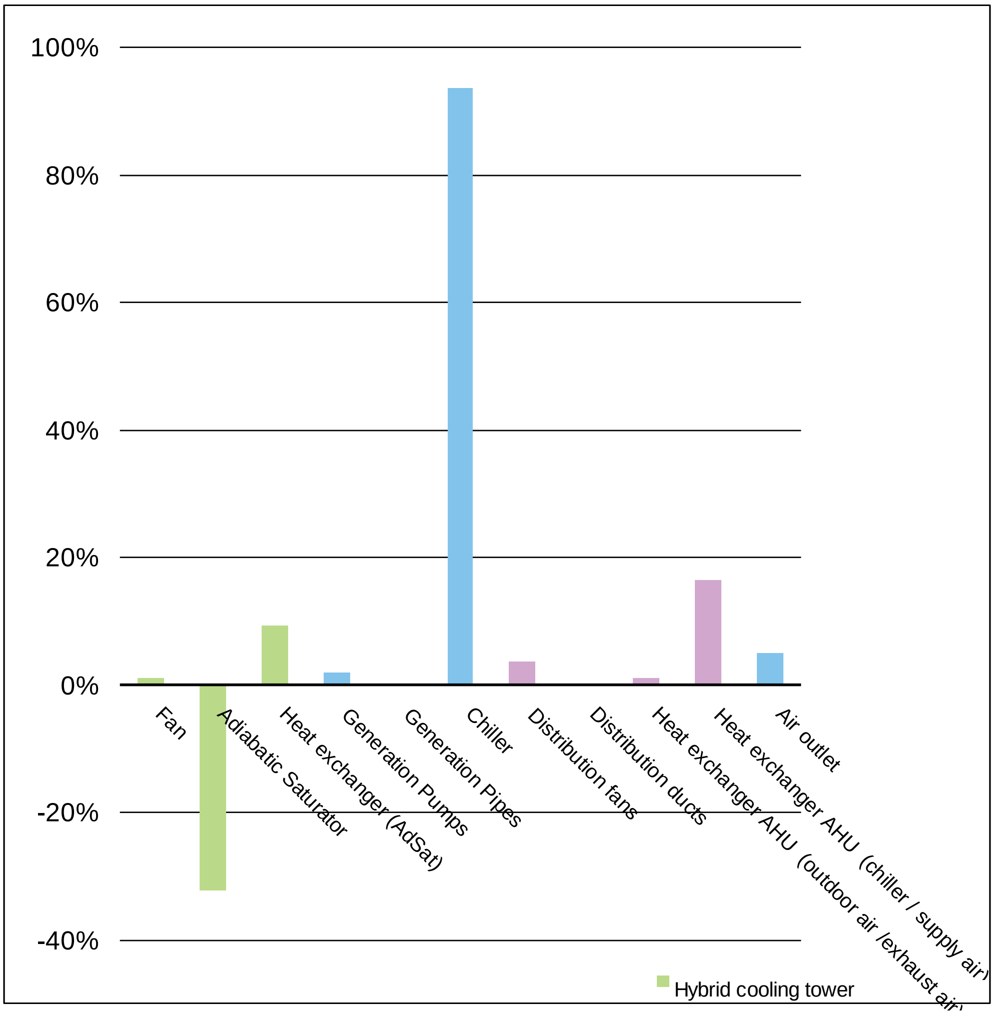

Figure 17: Exergy losses along the component chain for System 3

Exergy losses	Fan	Adiabatic Saturator	Heat exchanger (AdSat)	Generation Pumps	Generation Pipes	Chiller	Distribution fans	Distribution ducts	Heat exchanger AHU (outdoor air /exhaust air)	Heat exchanger AHU (chiller / supply air)	Air outlet	Total
[W]	100	-2800	810	170	8	8100	320	10	90	1430	430	8670
	1%	-32%	9%	2%	0%	93%	4%	0%	1%	16%	5%	100%

Tab. 9: Exergy losses in the component chain for System 3

Here as well, it is clear that the chiller causes the greatest exergy losses. In this case, the exergy gained from the outside air by the adiabatic saturator makes up for less than half of the losses in the chiller.

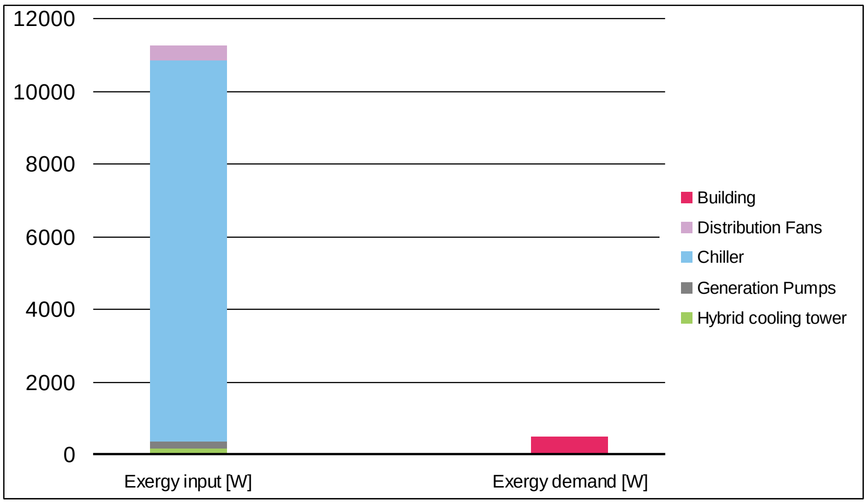

Figure 18: Exergy input and demand for System 3

	Hybrid cooling tower	Generation Pumps	Chiller	Distribution Fans	Building	Total
Exergy input [W]	150	200	10500	400		11250
	1%	2%	93%	4%		100%
Exergy demand [W]					460	460

Tab. 10: Exergy input and demand for System 3

The resulting exergy efficiency for the air cooling system is 4%. This is the lowest of the three calculated systems.

2.5 Discussion and conclusions

Exergy analysis can be used as a tool to minimise the environmental impact caused by the use of different energy sources, regardless whether the energy sources are renewable or not. Exergy analysis visualises the efficiency of a system. If a system has an exergy efficiency of 20%, there is 80% more to gain from that system. However, although renewable energy sources such as outdoor air, geothermal or solar energy have an exergy content, their environmental impact can be considered very small. In this report, we therefore consider renewable energy sources as containing free exergy. The components used to convert the renewable energy into energy useable for room conditioning however, need to be optimised to ensure the most efficient use of the energy sources. Therefore the exergy losses in the components are calculated.

Exergy gain by the adiabatic saturator from the outside air is regarded as free exergy. It therefore does not add to the exergy input when regarding the overall exergy efficiency of the systems. The same is true when considering a system with a borehole. The exergy extracted from the ground is considered free exergy. The exergy gain is instead visible in the display of losses throughout the system chain and is accounted as a negative loss.

Overall it can be concluded that all three systems have a low exergy efficiency. Keeping a comfortable indoor climate in highly insulated buildings, through cooling or heating, is not a high exergy process in itself. The exergy demand for the building is low. The reason for the low exergy efficiency of the three cooling cases is that the primary energy source is electric energy, with an energy quality factor of 1, thus being 100% exergy unlike waste heat which would have a much lower quality.

The main losses occur, as expected, in the chillers and the heat exchangers. The fans and pumps in the three cases do not have high exergy efficiency (10-20%), but the fraction of their losses in comparison with the total is low. For the three calculated cases the greatest optimisation potential lies in the system configuration and in the components heat exchangers and chillers.

The system with the highest exergy efficiency in the analysis is system 2. Water, instead of air, as the energy carrier is an important precondition. Also important is the production of cold water at a temperature that can be directly distributed to the floor cooling, without the use of a heat exchanger in between. The production of high temperature cold water gives a lower temperature lift in the chiller and consequently a high COP. The absence of a heat exchanger eliminates the exergy losses that would occur there, on one hand because of circulation losses and on the other due to the inevitable temperature difference between primary and secondary side outputs.

It is well known that water is a better energy carrier than air. In these examples it is also shown that a system configuration that allows for direct distribution of the chiller output to the emission system doubles the exergy efficiency in comparison with a system where an intermediate heat exchanger is necessary. The difference in exergy efficiency between Systems 1 and 3, however, is small.

Another interesting result is the display of the exergy potential in the outdoor air at mid European humidity conditions. For System 2, the exergy gained from the outdoor air is in the level of the losses from the chiller.

The steady state calculation shows the exergy flow in the system in a given instant. Thereby it is possible, with minor input changes, to create an overview and compare different system states. The quick response and overview is very useful in a first stage of system design. The exergy analysis serves as an important complement to traditional energy performance evaluation.

In this report the use of SEPE as a tool for exergy analysis of cooling cases has been shown. The tool can be used to optimise a single system, to show the effect of system changes, and to compare different heating or cooling systems in a first stage of design.

SEPE, including the above examples, are available for download at http://www.annex49.com.

Further calculations and evaluations with SEPE, mainly for the heating case, can be found in [4].

3 Contribution to Subtask C: Wastewater heat recovery exergy analysis

3.1 Introduction and Motivation

Wastewater heat recovery is the logical next step in the evolution of high performance buildings. A common problem for modern high performance buildings is that although the space heating demand is minimized, the energy demand for warm water remains the same. This is due to the fact that historically space heating creates the largest energy demand. Therefore is has been the focus of improvements. This is illustrated in Figure 19. As water-heating demands have remained rather constant and space-heating demands have been reduced, the significance of what was formerly the third largest energy demand grows to become the largest demand. In passive houses, often the domestic hot water heating becomes the most significant source of total energy demand. For this reason it is important to evaluate the potential of capturing or recovering wastewater heat.

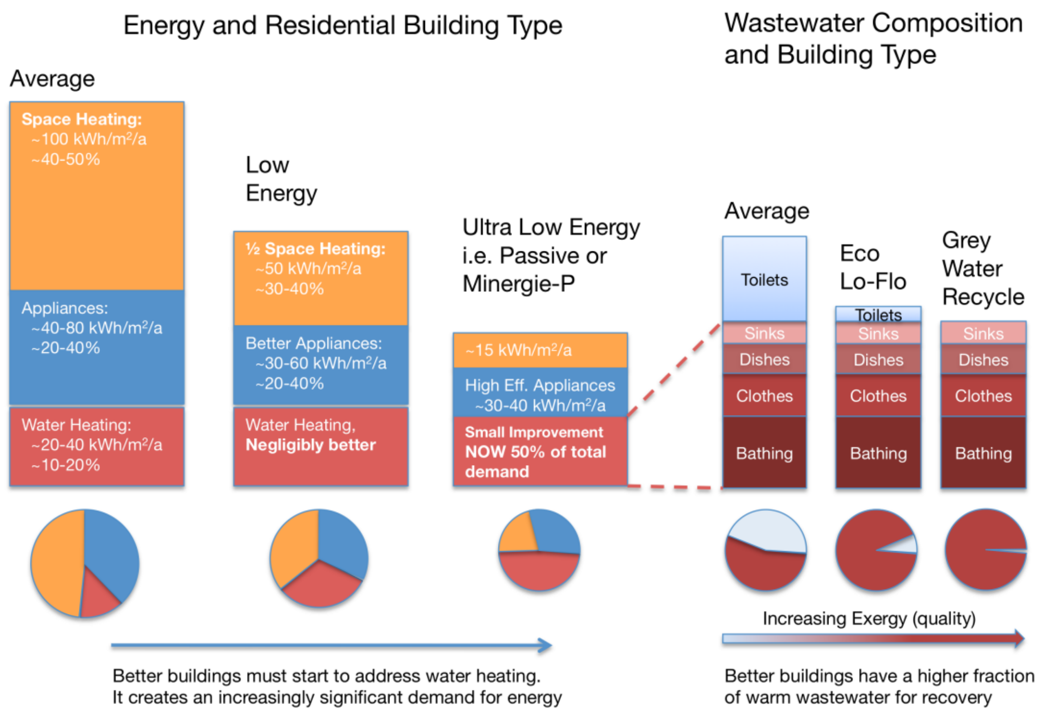

Figure 19: Hot water energy demand and exergy potential. Illustration of the significant increase in the fraction of total energy demand for buildings coming from hot water as building performance increases (left), as well as the increasing quality in the wastewater as improved sanitary installation are used (right). [11]

Not only is there a significant energy source being lost in wastewater, but there is also a significant exergy potential. Again in Figure 19, as the hot water heating demand becomes a part of high performance systems, such as ecological low flow systems or grey water recycling systems, the fraction of the water that is used at cold temperatures is reduced. Therefore the average temperature is increased causing the exergy content to increase. In fact, for a grey water recycling system, the sources that are captured for water recycling can serve a double purpose because theses are also the sources where hot water is used.

The density of water as compared to the other primary heat carrier in buildings, air, is 1000 times greater. Also, the wastewater is at a higher temperature than the space heating. Yet heat recovery from exhaust ventilation is a common practice, whereas wastewater heat is rarely considered for recovery.

This analysis strives to evaluate the maximum potential of wastewater as a heat source. It does so by considering the exergetic value of the wastewater at the point of use. The models that have been implemented capture wastewater in a decentralized concept that focuses only on sources where hot water is used. We imagine a system that is part of a separate wastewater flow from showers, baths, sinks, clothes washing, and dish washing.

By integrating a low temperature-lift heat pump we can maximize the COP of the system, because the wastewater provides a high temperature heat source. This provides the potential for a low temperature-lift for the production of hot water water, even up to 55 °C, which is often a problem for low exergy systems. Therefore this system can play a valuable role the overall low-exergy building concept, for example when added to the systems described in [12-14].

The project began with a look at the previous work that has been carried out for heat recovery from wastewater sources. Then some initial concepts for the system were drawn up. The initial models were done on the tank aspect alone and then finally, the integrated operation of a heat pump was incorporated into a final model. The results were presented in a series of papers that were generated during the course of the project, which are cited in subsequent sections describing the work.

3.2 Previous work in wastewater heat recovery

Although the recovery of heat from wastewater has not been implemented in a large number of projects, the concept does exist and has been implemented and studied in a variety of scenarios. In general, the exergetic potential of the warmer wastewater near the source is not considered, but some systems do recognize the benefit of incorporating gray water recycling systems.

The FEKA system is a large scale wastewater recovery system that utilized the large mass and mixed flow of wastewater from a large number of dwellings, or for example, hotel rooms, to create a higher temperature thermal source for the integrated heat pumps. It was described in one implementation as providing 8,000-10,000 L of hot water per day at 60 °C and recovering wastewater heat at 23 °C [15]. The FEKA system improves the performance of the overall system, but does not reach the full potential that could be provided by the high temperature hot water coming from sources before they are mixed, because although a significant amount of energy is recovered, a significant amount of exergy is lost.

There have also been studies, specifically one coming from the SFOE, that look at the potential of heat recovery from the sewer channels. This system is again connected to heat pumps that can use the heat and average temperature of 10 - 15 13 °C [16]. In this case the wastewater is at an even lower temperature, but the source is very constant and reliable.

One of the obstacles faced by the decentralized system that we present here, is that the source is very stochastic and difficult to predict. Both the FEKA and any system extracting heat from the sewer overcome this problem by utilizing a large number of inputs so that a regular input can be anticipated. This facilitates the design of the system, but at the same time causes significant losses in potential exergy recovery because the recovery flows are mixed and have decreased temperatures.

Still, there have been studies that consider the potential of heat recovery from gray water systems. They show that direct heat recovery from the grey water system can produce a significant reduction in the domestic hot water heating demand. In one case the hot water heating demand was reduced from about 5300 kWh/yr to 4500 kWh/yr, or a reduction of about 15% [17].

Finally, the integration of heat pumps into hot water supply is also a readily available technology. Many of these systems actually use exhaust air as a higher temperature heat source. The performance of such systems have been analyzed in [16]

3.3 Design concepts

The initial concept was developed in collaboration with Prof. Dr. Hansjürg Leibundgut, the head of the Building Systems group at the ETH Zurich. As stated, the idea was to find a way to minimize the temperature lift of a heat pump for all operations in a building, which included hot water heating. The first concept then illustrated how a dual-mode heat pump could be designed to operate with two similar temperature-lifts, but with two different source and sink temperature pairs. One would provide low-temperature space heating with the constant source of a borehole, while the other would provide higher-temperature hot water heating using the warm wastewater heat recovery as a source. This is illustrated in the preliminary diagram shown in Figure 20

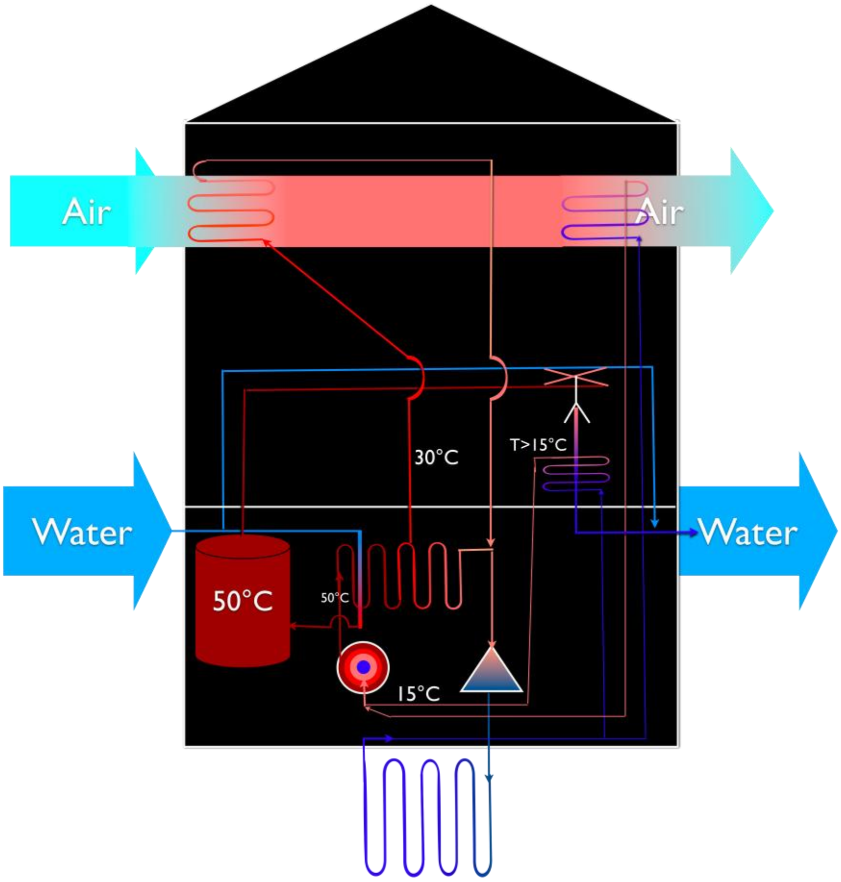

Figure 20: Diagram showing the initial concept for the heat recovery using a dual-mode heat pump with a compressor that could switch between two different temperature levels of operation depending on the supply of wastewater heat. Here, the system is depicted as providing 50 °C hot water when a source of wastewater above 15 °C becomes available, while at the same time constantly providing air heating at 30 °C and also utilizing exhaust air heat recovery.

A second concept looked further into the various temperatures available to the system. It also considers how a combined heat pump with high COP could minimize the electricity demand of the system, making PV integration more feasible for a building with a goal of zero operational CO_2 emissions. This is shown in Figure 21.

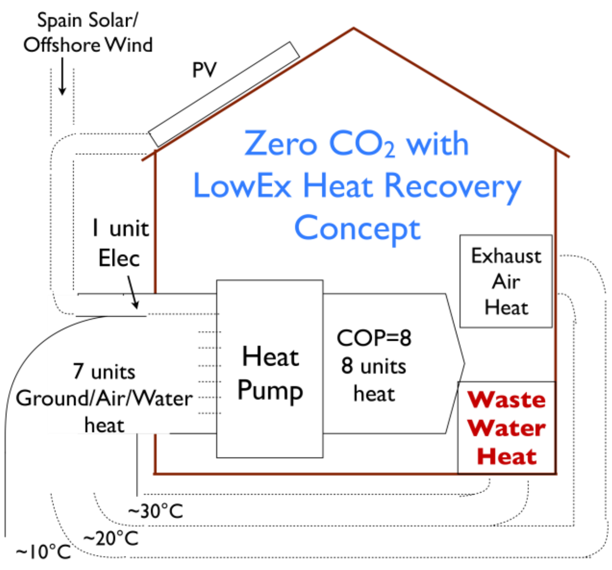

Figure 21: Conceptual depiction of the potential of heat recovery systems on the performance of a heat pump and the subsequent reduction of its energy demand as a result of higher COP. The COP for hot water production would be increased most by the use of wastewater heat at a temperature of around 30 °C.

3.4 Initial modeling and results

The model for recovery from wastewater was evolved over the time span of the project through many model iterations. The initial model focused on the operation of the recovery tank itself and the amount of exergy that can be extracted with various sizes and heat exchanger flow rates. This model was expanded to evaluate the effect of a stratified tank compared to the initial model that assumed mixed conditions. These models were than evaluated for a larger set of housing conditions and a new tank model was considered that simplified the heat exchanger design.

One of the universal obstacles for studying heat recovery from wastewater close to the point of use is the stochastic nature of the input. Unlike the large systems, or systems integrated with the sewer, this decentralized system must deal with each event individually. In this case a batch operation has been assumed where a tank receives each event and extracts heat from the wastewater. In the case of recovery from near the point of use, as in our decentralized, high-temperature heat recovery concept, the details of the stochastic input to the tank are important to its design and performance. The nature of the operation makes it important to find accurate data for input into the model to generate a realistic wastewater profile, and analyze realistic operation. Unfortunately, there is no specific data for wastewater flows on the timescale necessary to analyze heat recovery. Therefore, hot water usage data was used, assuming a certain flow and temperature to produce a wastewater input to the system. For Switzerland there are some average data on wastewater usage [19], but for this system a more detailed dataset is used. This was acquired from statistical models from Germany and from the USA to generate hot water loads used to analyze building performance, specifically in the case of solar heating systems [20-23]. The initial analyses al used a continuous dataset with 6-minute time steps for the entire year describing the flow rate at each point in time.

For all of the models an iterative approach is used. The wastewater is input into the tank and a heat exchanger model is used to calculate the heat that can be extracted. The temperature, energy, and exergy are calculated for series of realistic wastewater inputs generated from the datasets described above. Once a yearly simulation is made, the various parameters of the system are varied and the simulation is repeated to observe the change in performance. These design parameters can also be iterated to search for any optimal values.

For the first models that just explored the tank independently the methodology was as described in [24]:

> An energy balance was performed on the system at each 6-minute time-step for the data from [20-23]. The heat exchanger energy balance allowed the determination of its exit temperature as well as the new temperature in the tank. The tank temperature was assumed to be constant over the time step and the spiral heat exchanger was assumed to act as a pipe in a medium of constant temperature. The natural convection was neglected in order to analyze the worst-case of simple conduction. Equation 9 determined the outlet temperature, T_{out}, of the heat exchanger at each time-step based on the current tank temperature, T_{∞}, the entering water temp, T_{in}, and the properties of the system (density, ρ; flow rate, Q; heat capacity, c_p; tank diameter and width, D_{tank} and L_{tank}; and the convection coefficient, h, based on the Nusselt number, Nu; heat transfer coefficient, k; and the pipe diametere, D_{pipe}).
>
> (9) $$T_{out} = T_{\infty} - e^{\frac{-h_{fluid}(\pi D_{tank} L_{tank})}{\rho_{fluid} Q_{fluid} c_p}} * (T_{\infty} - T_{in}) \text{ where } h_{fluid} = \frac{Nu * k}{D_{pipe}}$$
>
> The outlet temperature allows the energy extracted to be calculated as well as the new tank temperature. This is then repeated over the year for all the warm wastewater events to determine the performance.
>
> Within each time step a check was made to ensure the validity of the constant temperature (quasi steady state) assumption. If the temperature changed by more than 2 degrees in one 6-minute step, a subloop was run within that time to maintain validity of the assumption.
>
> The exergy analysis used a simple assumption for an incompressible fluid to determine the exergy removed by the heat exchanger at each time step. Equation 10 describes the exergy value, Ex of the water exiting the heat exchanger. The total heat Q_{out} subtracted by the environmental temperature T_{env}, which was set at 5°C, and is multiplied by the change in entropy represented by the natural logarithm of the average tank temperature between the two time-steps, $T_{tank,ave}$ and the heat exchanger input temperature, $T_{in,HX}$
>
> (10) $$Ex = Q_{out} - T_{env} * \ln\left[\frac{T_{tank,ave}}{T_{in,HX}}\right]$$
>
> The final aspect of the analysis involved the integration of the recovered exergy into a low exergy building system. This means evaluating the impact of the potential recovery on the performance of a heat pump that is required to supply hot water. This was done by evaluating the potential improvement to the COP based on Equation 11 where the supply temperature is the demanded hot water supply temperature and the available temperature is what can be provided by the heat recovery system. This was compared to the performance of a typical electrical and natural gas boiler systems.
>
> (11) $$COP = \left\lfloor \frac{T_{Supply}}{T_{Supply} - T_{Available}} \right\rfloor$$

The full details of each analysis are provided in the papers that will be subsequently described.

3.4.1 Static modeling of a recovery tank

The first model was built to analyze the amount of heat and also the amount of exergy that could be captured by a tank connected to a one-family residence with three different sizes.

The data was generated from the statistical software [21] to create a hot water annual usage profile described by [22] for the three scenarios of a 2, 3, and 4-bedroom residences. The operation was assumed to be a batch mode where each event was captured and then cooled down to a set temperature. The tank was assumed to be cylindrical with a spiral heat exchanger inside. The total energy and exergy that could be recovered from the tank along with the potential temperature that could be supplied to a heat pump were calculated.

Two papers were presented using this model. The results showed an interesting outcome that by using an exergy analysis, optimal points of operation are shown for certain tank design parameters, which would otherwise not be discovered by an energy analysis alone. The full description of the methods and analysis are given in [25, 26]. The following results are extracted directly from these two studies.

Results from [25, 26]:

The dynamic filling and emptying of the of a 600 L recovery tank for each 6 minute time step over the model year is shown in Figure 22. The variations shown are due to complete emptying of the cooled tank, while the overflow happens only while the tank is completely full.

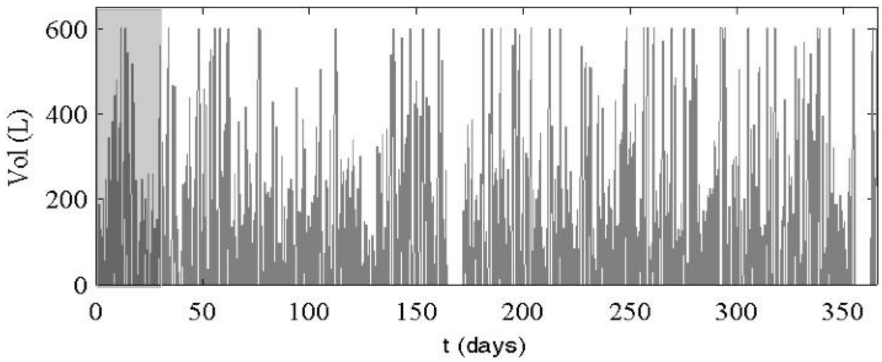

Figure 22: Volume in the recovery tank over the course of the modeled year with the month of January highlighted.

January is highlighted in Figure 22, and is shown in Figure 23. The top plot shows the total volume as well as the overflow volumes. The middle is the tank temperature. The bottom is the exergy output based on an environmental reference temperature of 5 degrees Celsius.

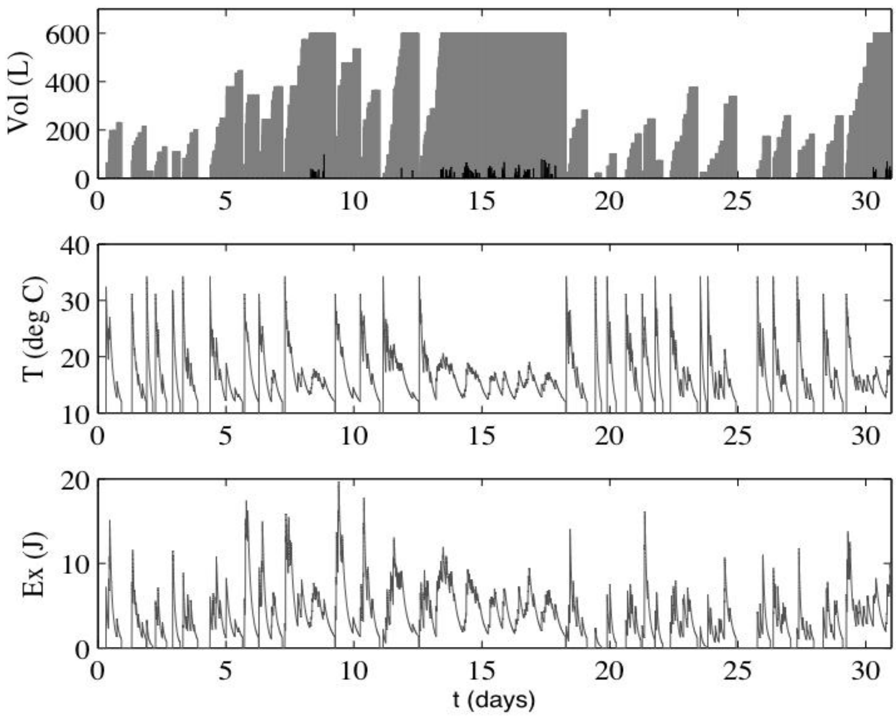

*Figure 23**:** January data for the recovery tank total volume (grey) and overflow volume (black) on top, tank temperature in the middle, and exergy recovered on the bottom.*

It is clear that a normal fill and recovery cycle takes about one to two hours. The exergy recovered follows the temperature with an order of magnitude greater amount being extracted at steps when the tank is fresh and warm.

The heat exchanger flow rate was adjusted to optimize the total exergy recovered over the year. This proved that a flow rate of 1.3 L/min was optimal as shown in Figure 24. This maximum was then check across different tank volumes and it was found to be consistently within 0.1 L/min of this value.

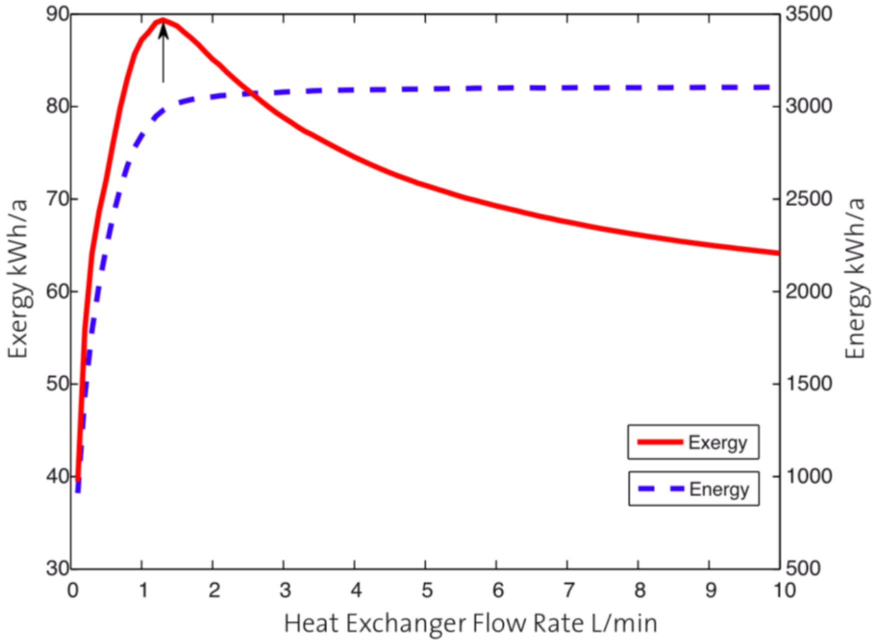

Figure 24: Total exergy recovered over the year versus the heat exchanger flow rate.

The exergy output was also observed for the different values to find the optimal tank size, as shown in Figure 25.

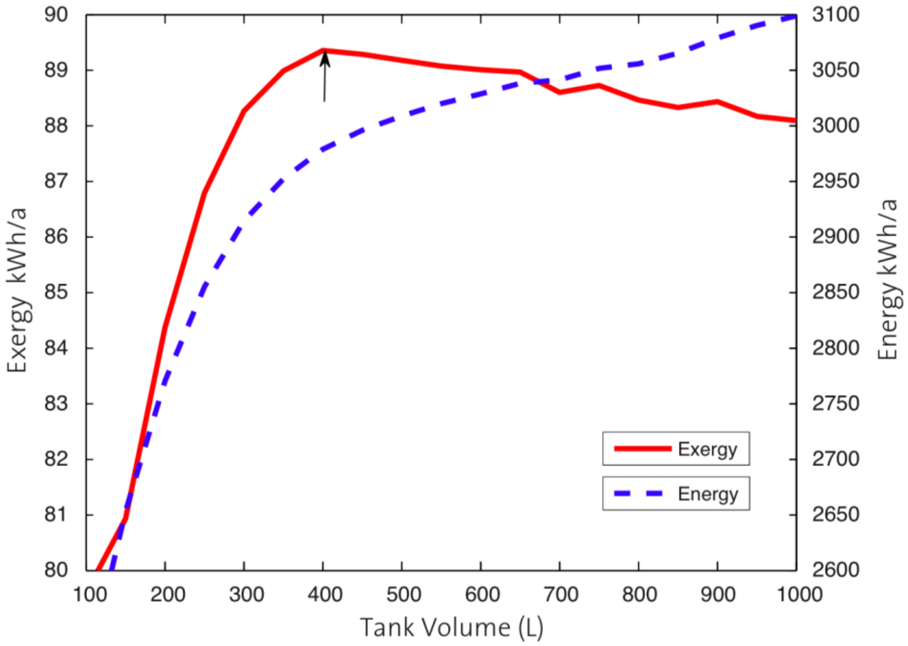

Figure 25: Total exergy recovered over the year versus the size of the tank for the flow rate of 1.3 L/min.

In Figure 4 there is also a maximum for exergy recovery based on tank size that is not shown by the energy output. In this case it is less pronounced, and it is for a 400 L tank. In this case the energy output continues to rise for larger tanks, but not at a significant rate.

Both maximums were consistent when adjusting other system parameters. The maximum recovery was 89 kWh of exergy and 3000 kWh of energy. On the basis of energy the 3000 kWh is about 70% of the energy in the hot water use for a year. From an exergy perspective 85 kWh are recovered compared to the 350 kWh supplied. This is only 25% because the temperature recovered is lower than the temperature supplied, thus the exergy describes a loss in quality. But this view of quality allows for these optimal points to be discovered, whereby more high quality energy can be recovered at higher temperatures not just to be transferred to a heat pump, but also to improve its performance.

A simple comparison to heat recovery from exhaust air demonstrates the relative significance of wastewater recovery. For the 4- bedroom case, the assumptions for exhaust air are five people with 30 cubic meters per person, and a temperature of 25 degrees Celsius. Making the approximation that air is heated for 5 months from 10 degrees Celsius and using the same reference conditions as used for the water, the total exergy in this stream is about 100 kWh (0.36 GJ). This is an approximation, but it is clear that the potential from wastewater is on the same order of magnitude or higher.

The potential recovery of exergy from hot wastewater has been analyzed. There is an optimal savings in a year for a typical 4-bedroom residence of 85 kWh (3.1 GJ/year). This is for 68% recovery of heat, but is 25% of the exergy. A potential concept for integration of this system is presented and an estimate of the performance increase in the heat pump during recovery is shown to increase the COP significantly with a potential to nearly double the performance during high temperature recovery outputs.

3.4.2 Extension to a stratified model

The initial model was then extended to observe the potential effect of allowing stratification in the recovery tank. The initial model made a simple assumption that the tank was fully mixed with uniform temperature and that when multiple events overlapped, they could simply be combined using an energy balance. For the stratified model, when multiple events occurred they were stacked on top of each other, and the setup of the heat exchanger was such that it encouraged the warmer temperatures to be at the top of the tank. This allowed for higher temperature heat to available for recovery even when a cooled wastewater event was mixed with a new warm wastewater input. Since the goal was to maximize the exergy recovery, which is dependent of the temperature, the stratified model allowed for a higher potential for exergy recovery.

The input to the model was identical to the initial model and the tank setup was the same. Due to the complexity of the model iterations, the calculation time for an annual iteration prohibited a full annual iteration across the various tank sizes to evaluate this design parameter. Thus the exergy optimization was done just for the month of January. The full methodology and results were presented in a paper and the results are quoted below [27]

Results from [27]:

> The stratified tank model required much more computation time, and due to small variations in the filling of the top layer, the long simulations were not always stable. Therefore the month of January was used to explore various flow rates for the optimal heat exchanger setting, instead of using an entire year. This is shown in Figure 26.

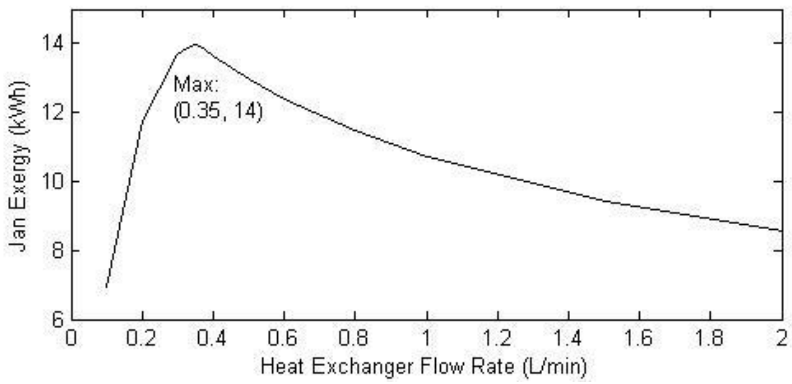

Figure 26: Exergy recovered over the month of January versus the heat exchanger flow rate

> The total exergy consumption for the entire year was computed on an individual basis for this optimal flow rate of 0.35 L/min and also for 0.3 and 0.4 L/min to check that it is still a maximum for the whole year. The values for 0.3, 0.35, and 0.4 L/min were found to be 146.0, 147.4, and 147.0 kWh respectively. Thus 0.35 L/min is probably a good estimate for the maximum.
>
> Compared to the mixed tank model this is a much lower flow rate. However, this should be expected as the stratified model allows higher temperatures to be present and remain longer in the top of the tank. The heat exchanger flow gain more exergy from the high temperature fluid at the top using a lower flow rate.
>
> As for the quantity of energy recovered in the stratified tank, it is the same as the mixed tank at 3000 kWh hours of energy, or 68% of the hot water energy recovered. This agreement helps to verify accuracy of the independent models.
>
> As expected, the exergy recovery is higher because a higher temperature is maintained at the top of the tank. By routing the heat exchanger from the bottom of the tank to the top, a stratified system is setup that helps increase the quality of the

energy extracted. In this case 145 kWh of exergy are recovered from the original 350 kWh, nearly double that from the mixed tank model.

3.4.3 Analysis of multiple dwelling sizes

Because the data input for the first studies [24-26] was only based on a single residence with various assumptions about the number of occupants (2-4 bedrooms), a further analysis was carried out for a wider variety of residence sizes. In this case the statistical domestic hot water software tool (DHWCalc from The University of Kassel) [21] was used to generate one year of hot water events. This was done for a one, two, four, six, and eight family building using typical weekday and weekend probabilities for shower, bath, sink, clothes washing, and dish washing events.

The impact of the system is evaluated compared to natural gas and electric hot water heaters. The electricity price is taken to be about 0.20 CHF/kWh and the gas price is 0.74 CHF/kWh. The greenhouse gas emissions for electricity are taken from the UCTE European average of 0.47 kg-CO_2/kWh and for natural gas combustion it is 0.25 kg-CO_2/kWh. Assumptions had to be made for the operation of the recovery tank. Some parameters were fixed such as the cylindrical tank shape, while others like volume were varied optimized for maximal exergy recovery. Results below are taken from [24].

Results [24]:

Figure 27 shows how the potential exergy recovery was analyzed for different sized tanks for the various building sizes. This was also done for the heat exchanger operation, which provided an optimal flow rate to minimize exergy destruction from high temperature differences. These specifications were then used to calculate the annual performance and potential savings of the system compared to the standard systems.

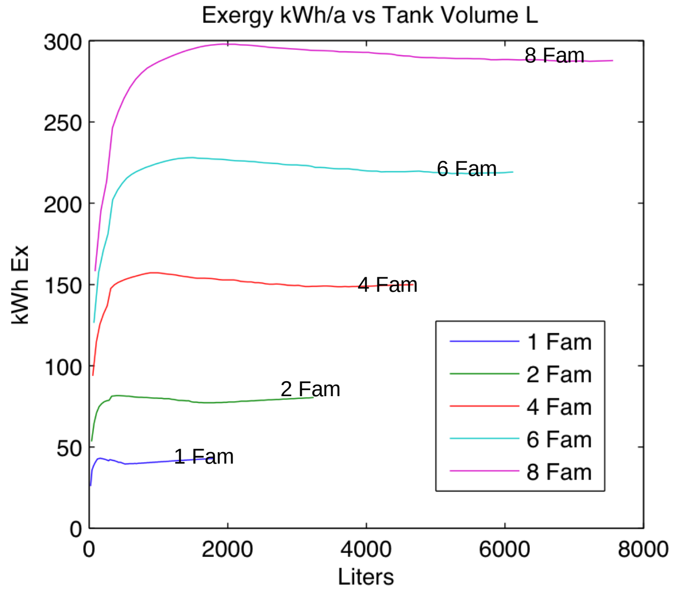

Figure 27: Tank Size exergy recovery optimization for different sizes

The savings are about 1500 kWh per year per residence. This is for an input of about 3000 kWh per year for hot water at 50°C, and when the wastewater is assumed to be 30°C that translates to about 1,700 kWh per year available to recover. The large majority of the energy is lost when one assumes a 30 degree mixed recovery. Of the 3000 kWh it is assumed that only 1700 kWh are available for recovery. The system thus recovers around 90% of the heat available in the wastewater.

The recovery translates into different levels of savings that depend on the type of heating system and the way the recovered heat is exploited. The heat can be most easily used directly to preheat water, which in turn directly reduces the demand on the system in place. In this analysis we've looked at a standard natural gas and standard electric boiler. The natural gas boiler is cheaper to operate so the cost reductions from direct heat recovery are less. They are about 100 CHF/a per residence vs the electric boiler using more expensive electricity saving about 285 CHF/a. The emission reductions also vary depending on both the boiler type as well as the source of the electricity (CH vs EU). The CO2 reductions thus range from about 180 kg per residence for a Swiss electric boiler to 700 kg for a European electric boiler with the natural gas savings falling in between at about 375 kg.

The savings can be greatly increased when integrated into a heat pump system for heating. Based on Equation 3, the heat pump COP could be increased easily from 4 to 8 with appropriate compressor technology that maintained the Carnot efficiency, η_{Carnot}. The value of the higher temperature (more exergy) warm wastewater recovery can greatly improve the performance of the system. In the case of integration with a heat pump system, the savings mentioned above are doubled with 1,300 kg of CO2 being eliminated and 550 CHF of cost reduction for an electric boiler.

3.5 Final model including heat pump operation

The wastewater heat recovery project culminated with the development of a final model that incorporated an analysis of the real-time operation of an integrated heat pump with the heat recovery tank. The potential operation of the system in two potential application modes is considered. In one application the system recovers heat from all sources in a combined mode and the heat pump utilizes the heat in the recovery tank until the tank reaches a set temperature. The second mode ties the heat pump output directly to the hot water demand, and the heat pump extracts heat only from the sources found in the bathroom, then directly supplies the heat back to the hot water storage.

This final analysis used a new improved dataset [23] that provided a list of events with times and durations. This eliminated the limitations presented by the 6-minute time interval, and also reduced the simulation time because not every 6-minute step had to be analyzed. The data was also improved statistically to account for increased probability of events like showers being grouped together in the morning. This is especially important for our model, in which the impact of overlapping events plays a significant role.

The final analysis also considers a different tank and heat exchanger design. One problem that is foreseen for the operation of the tank is organic fowling of the heat exchanger. In order to simply the potential cleaning of such a system and to minimize the small surfaces areas in a spiral heat exchanger, a cheese-kettle style tank was considered, in which the heat exchanger is installed inside the tank walls. This was considered as part of the progress toward the production of a pilot, which was initiated in a KTI project with Geberit AG. The analysis of the system was based on free convection models to estimate the heat transfer coefficient [28]. The complete free convection and heat exchanger analysis results are presented in a summary provided to Geberit in Appendix 2.

The simulation and analysis are part of a paper that is currently being submitted for publication. The paper methods and results is given below [29]:

3.5.1 Methods

The heat extraction from the tank is done using a new model for heat pump operation. Two versions of this model have been studied: one that recovers heat simply based on the temperature of the wastewater and one that recovers heat to directly regenerate the hot water supply system. For both versions we take a heat pump and fix its condenser temperature for the supply hot water back to the domestic hot water storage tank. This was fixed at 55 °C, but could be varied. The evaporator temperature is set to follow the tank temperature with a temperature difference of 5 K. This type of heat pump control would be possible with an electronic expansion valve and a variable speed compressor. This allows the temperature-lift of the heap pump to vary with the tank temperature and maximize the potential COP. It also simplifies the calculation for heat extraction, as the tank temperature will fall linearly assuming a constant temperature difference between the wastewater source and the heat recovery fluid as well as a constant heat exchange surface area and heat transfer coefficient for each new event. The heat pump is assumed to operate with a Carnot factor, g, of 0.5, shown to be possible for heat pumps down to a temperature-lift of 10 K and a COP of 14, [30].

For each event the volume and temperature of the input to the tank are accounted for. The time since the previous event is checked against the time, *t_empty*, that it would take the tank to empty. This is calculated from Equation 12 with a selected tank emptying temperature, *T_empty*, by using an energy balance based on the old temperature, *T_old*, the fixed temperature gradient between the wastewater and the recovery fluid, *ΔT_hx*, the overall heat transfer coefficent, *UA_hx,* and the tank volume, *V_old*. If the there is sufficient time since the last event, then the heat extracted and exergy extracted from the last event are calculated using Equation 13 and 14 where *T_in* is the intial temperature of the tank and *T_out* is the emptying temperature of the tank, *T_empty*. If the time, *t_empty*, is greater than the time since the last event, *t_event*, then it is still extracting heat from a previous event when the next event occurs. In this case, the new partially cooled temperature, *T_new,* of the previous event is calculated based on the heat extracted since it was added to the tank using Equation 15. Also the energy, *En,* and exergy, *Ex,* extracted are recorded since the event was added, again from Equation 13 and 14. The new temperature, *T_new*, of the old event is then used to determine the new combined temperature of the tank, *T_tank*, using the energy balance in Equation 16, where *V_add* is the new volume added to the tank and *V* is the actual volume total for the event, in this case the combined total.

(12) $$t\_empty = T\_old - T\_empty*cp*rho*V\_old / (\Delta T\_hx*UA\_hx)$$

(13) $$En = cp*rho*V * (T\_in - T\_out)$$

(14) $$Ex = cp*rho*V* (T\_in - T\_out - T0 * \log(T\_in/T\_out))$$

(15) $$T\_new = T\_old - \Delta T\_hx * UA\_hx * t\_event / (cp * rho * V\_old)$$

(16) $$T\_tank= (T\_in*V\_add+T\_new*V\_old) / V$$

Once all the iterations have been completed we have a dataset containing the temperature and duration of each event. We have designed our system to minimize the heat pump temperature-lift by having the evaporator temperature follow the tank temperature. We know the amount of heat recovered and its temperature so we can now calculate the COP of the heat pump, and its subsequent potential heat supply and work demand.

The heat recovered, *Qc*, calculated in Equation 17, is constant throughout each event because of the constant recovery tank heat exchange temperature difference, *ΔT_hx* and the constant overall heat transfer coefficient, *UA_hx*, based on the free convection models [28] and surface area from the tank volume and geometry. The total energy recovered, *Qc*, is also dependent on the time, *t,* of recovery, which is either the time it takes to empty the tank, *t_empty,* or the time between events, *t-_event*, in the case that there is an overlap. The COP is a ratio of higher temperature heat supplied, *Qh*, to work input, *W*, but also based on the 2nd Law of Thermodynamics can be defined as a function of the Carnot factor, *g,* and its temperature lift, ΔT, as in Equation 18. We have fixed the warm heat pump supply temperature, *Th*, so the only time-dependent variable is the cooler evaporator temperature, *Tc*, for recovery, which can be defined linearly as above in Equation 15 for *T_new*. Therefore we can integrate the COP function over the duration, time, of each heat recovery event to determine the actual average operational heat pump COP, *COPave*, over that time period, Equation 19.

(17) $$Qc = \Delta T\_hx * UA\_hx * t$$

(18) $$COP = Qh/W = 1 - Qc/W = g * Th/(\Delta T), \text{ where } \Delta T = Th - Tc$$

(19) $$COPave = g * Th/k1 * [\log(Th - Tc + k1*t) - \log(Th - Tc)] / t$$
$$\text{where } k1 = (\Delta T\_hx * UA\_hx) / (rho * V * cp)$$

From the operational COP we can then take a time-weighted average over the year and determine the annual performance. This also allows us to determine the amount of heat that can be supplied and what amount of work (i.e. electricity) it will take to supply that heat using the heat pump as calculated in Equations 20 and 21.

(20) $$W = (1 - Qc) / COPave$$

(21) $$Qh = COPave * W$$

Based on the input data for hot water usage we also know the amount of heat supplied at each event, and thus the amount that needs to be replaced in the hot water storage. This is calculated in Equation 22. It is based on the volume of hot water supplied and its temperature compared to the temperature of the cold water supply from the municipality mains, which varies over the year and for different locations. We used an arbitrary sinusoidal function for the mains temperature taken from the US DOE data [23]. With this calculation we can then compare the potential recovery of heat using the heat pump to the heat supply, *Q_demand*, that would be demanded for the actual hot water being used based on the volume added at each event, *V_add*, the temperature of each supply event, *T_supply*, and the mains temperature, *T_mains*.

(22) $$Q\_demand = cp * rho * V\_add * (T\_supply - T\_input\_mains)$$

This first application of the model works for the case when there are flexible heat demands and/or heat storage opportunities within the building because the heat supply is independent of any specific demand. For example, it could be representative of a full grey water recycling system where all non-toilet flows are captured. The amount of heat recovery is dependent on the set point at which the heat recovery tank is emptied. In this model an emptying temperature, *T_empty*, is chosen as the set point. The higher that temperature, the less heat is going to be extracted, but the higher the average COP because the heat pump will have a higher average source temperature, and thus a lower average temperature-lift.

The second version of the model involved an extension to match the heat recovery to the hot water demand. This eliminates the arbitrary emptying temperature, T_empty. Instead of selecting and emptying temperature, the system is set to run until hot water supply is regenerated using the recovery system heat pump. Specifically, the wastewater heat recovery supply from the heat pump, *Qh*, is matched to the heat demand for hot water supply, *Q_demand*. In order to determine the time needed to extract this amount of heat supply, an iterative solver is employed to find a solution to the non-linear equation setting the demand, Equation 22, equal to the heat supply, Qh, Equation 19, 20 and 21. This determines the time necessary for the system to run and the subsequent values of the average COP, heat recovery, heat supply, and work input. The extraction time is again checked for overlap with subsequent hot water events, and is combined with potential overlapping events in the energy balance described above. Thereby, we are able to evaluate the performance of a system that is designed to operate to exactly match the heat demand for hot water and replenish the hot water supply storage tank directly.

We can also use the recovery performance to optimize the parameters of the tank design. The design variables that impact the performance are the tank geometry and volume as well as the temperature at which the tank is emptied. The avoidance of overflows in the recovery tank as well as of complete emptying of the hot water supply tank are also considered. The model itself can be run iteratively to explore the impact of varying these parameters on the overall performance.

One of the principle variables to investigate is the sensitivity of the performance of the system to variations in the heat transfer rate, *UA_hx*, of the recovery tank with the heat exchanger in the walls. The heat transfer rate is calculated based on simplified models of cylindrical tanks filled with water experiencing free convection [28], which provide only rough estimates. The heat transfer rate can also easily be influenced by changes in the tank design and shaping. The walls of the tank could be designed to slightly improve the surface area, or the shape of the tank could be modified. These potential changes would all influence the heat transfer dynamics and thus variation in the parameter and the subsequent influence on system performance was evaluated.

3.5.2 Theory

The research into low exergy building systems instigated the development of this concept. By using exergy analysis, the appropriate value can be given to energy sources, which considers the value and potential of their temperature and not just their relative quantity of energy. This leads us to the development of systems that minimize temperature gradients and temperature losses, and not just the energy losses in the system. In the end, the heat pump provides the perfect heat supply structure for this system.

A heap pump, or chiller in the case of cooling, has a performance that is dependent on the temperature-lift it must supply as described in Equation 18. This is illustrated in Figure 28 where the non-linear benefit of decreased temperature-lift is depicted.

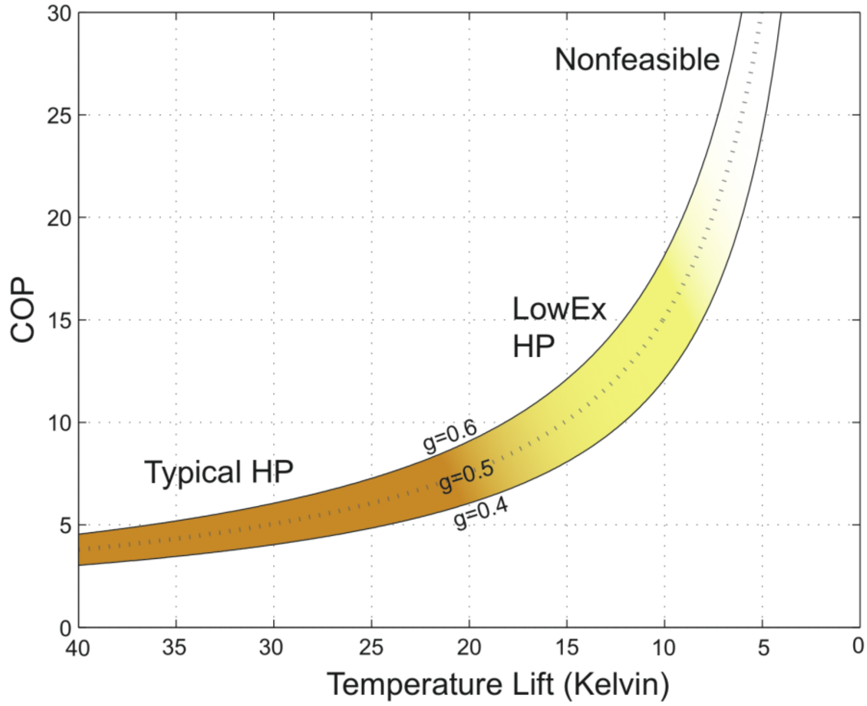

Figure 28: Figure 2: COP vs temperature-lift. Plot showing the change in COP of a heat pump as the temperature-lift is decreased. A range of Carnot efficiencies from 0.4 to 0.6 are plotted, and the area of desired low exergy performance is highlighted.

Low exergy building systems strive to reach performance levels that result in temperature lifts below 20 K. This allows heat pump performance to rise above 8 units of heat output per unit energy supply. Therefore, even if the primary energy factor of an electricity supply is not good, the heat pump more than compensates for this fact. This is often an obstacle for the current implementation of heat pump technology with COP values commonly ranging from 2.5-5, which in some cases cannot compensate for the primary energy factor, thereby making high efficiency boilers more effective on a primary energy basis, because the fuel is used directly without the losses associated with electricity generation and distribution. A heat pump has to overcome what is often a primary energy factor as high as 3 to match the primary energy demand of a boiler. But this is accomplished simply by designing systems with COP greater than 3. This can be achieved, and moreover, surpassed by low exergy systems with low temperature-lift demands.

Still, one of the biggest obstacles in maintaining this high performance resulting from low temperature-lifts is the supply of hot water. Hot water requires a higher supply temperature than space heating. Therefore the ways to minimize the temperature lift must be further considered. Many existing systems utilize exhaust air as higher temperature source for domestic hot water heat pumps [18], but this is limited in power and demand. The hot water has a high demand, but it is stochastic, and for this reason we consider potential of its own waste flow, in the form of wastewater.

Our concept of integrated low exergy system leads to a much higher potential of the overall system and a significant reduction in primary energy demand and subsequent greenhouse gas emissions. There are many systems that have been analyzed and are in various states of design, testing, and implementation [13-14]. The recovery of wastewater heat and its direct use in a heat pump use is one of these systems. The theoretical performance has been evaluated based on the theoretical operation of a heat pump, but this operation must still be verified. Nevertheless, the design uses only standard components and with the potential of readily available electronic expansion valves [30] and variable speed compressors, this type of heat pump control should be possible. It can be integrated into the overall low exergy system control as suggested by the first analysis where the system supplies an arbitrary heat demand, or it could also be part of a stand-alone hot water supply unit with heat recovery as supported by the second analysis where the recovery is matched to the hot water heat demand.

3.5.3 Results and Discussion

Recovery Model Independent of DHW Demand

The initial model that analyzed the potential for heat recovery, which would be independent of a defined demand, resulted in an annual average COP ranging from 5.5-7.5. The COP results were similar across the range of 2, 3, and 4 bedroom residence datasets. The COP range was dependent on the temperature chosen at which the tank emptied, *T_empty*. This temperature was varied from 15-30°C. The amount of heat recovered also depended on the temperature chosen for the of the recovery tank emptying. At lower temperatures, it is possible to recover more heat than is actually used to supply the hot water itself. This is due to the additional input of the work of the heat pump. This is shown in Figure 29, which plots the performance over a range of emptying temperatures. A larger amount of heat can be recovered when the wastewater is cooled to lower temperatures, but the performance, defined by the average COP, is higher if the emptying temperature is higher.

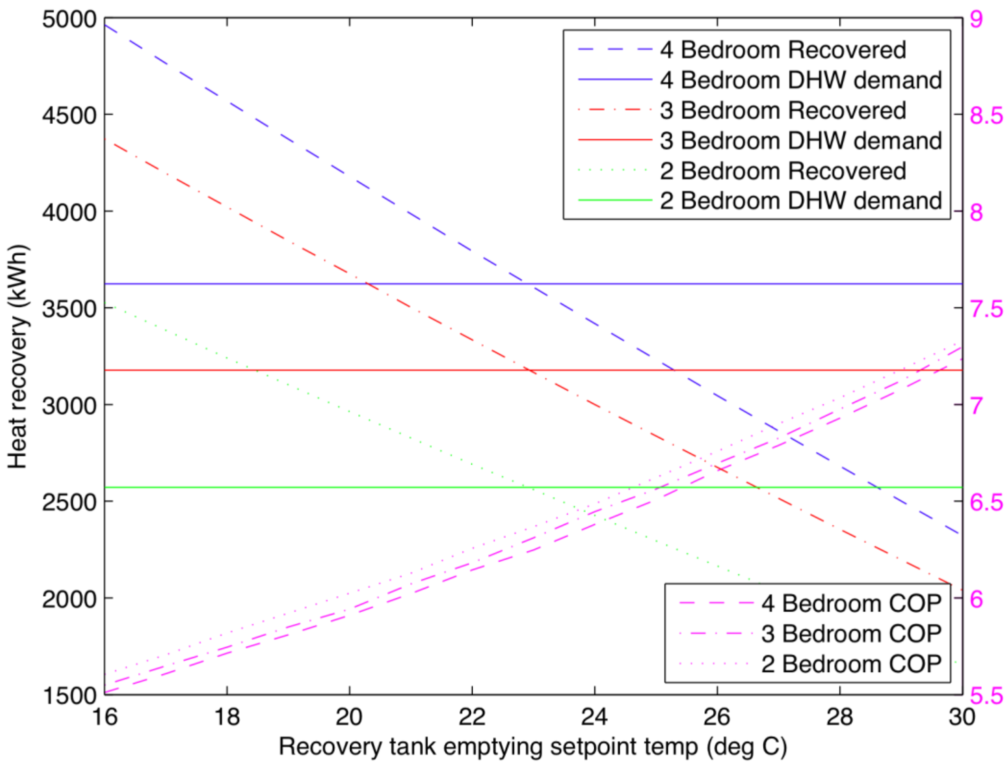

Figure 29: Performance for varying emptying temperature. The heat recovery and COP are plotted on two axis versus the tank emptying temperature. At lower recovery temperatures, a larger amount of heat can be generated by the heat pump shown by the recovery that can be larger than the actual demand. But the average COP of the operation is lower because the overall temperature is lower.

Figure 29 demonstrates how the higher temperature recovery benefits the average performance of the system. This can be viewed by comparing the energy recovered from the tank to the exergy recovered. In both cases the total amount is reduced as smaller amounts of heat are recovered, but as seen in Figure 30 the percent of exergy recovery remains higher as the temperature of recovery increases. This difference is caused by the increase in average recovery temperature, which also results in the increase in COP in Figure 29. The analysis of the exergy recovery from the tank [24, 25] allowed us to initially observe the higher potential of decentralized wastewater heat recovery, and to therefore connect a heat pump to the system to take advantage of this potential.

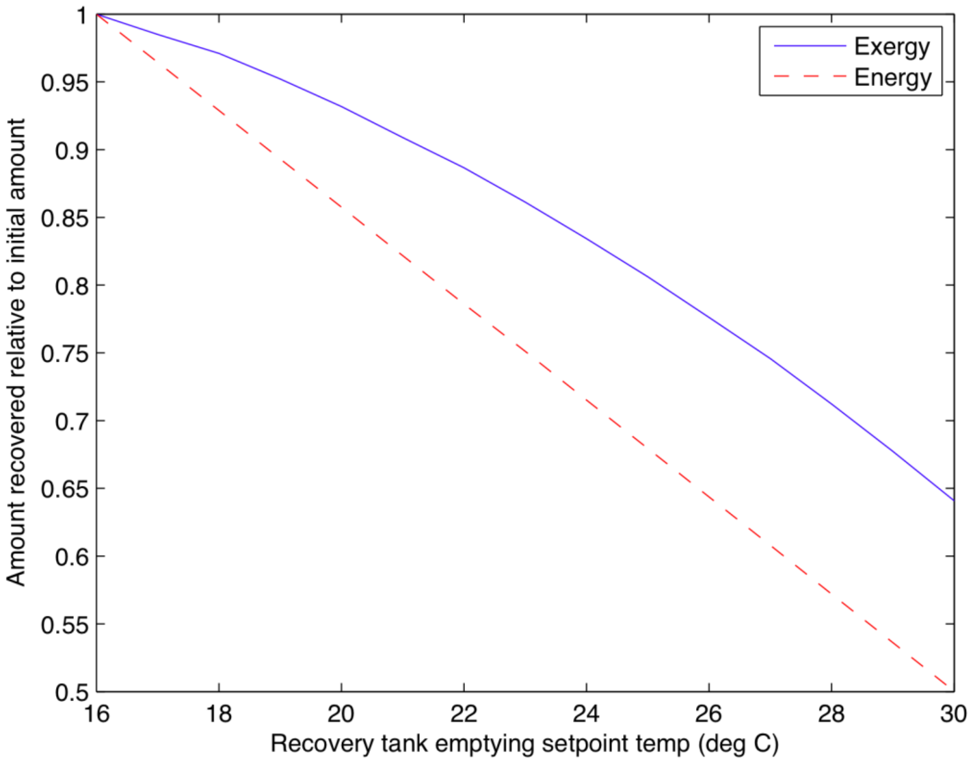

Figure 30: Energy and exergy comparison. Plot of energy recovered, also depicted in Figure 29, and the exergy recovered, both normalized to their initial value at a emptying temperature of 16 °C and based on the 4 Bedroom dataset. The increase in average temperature of the recovery causes the exergy to retain a higher value than the energy analysis does alone.

The heat pump achieves a high level of performance across all emptying temperatures compared to typical values for hot water heat pumps [18]. For example when the tank is emptied around room temperature, at 20 °C, a heating demand of 3300, 3800, 4400 kWh/year was provided with a heat pump demand of only 550, 690, and 790 kWh/year for each residence size respectively. This is a small amount of energy input compared to the typical energy demands for hot water that are on the order of 5000 kWh/year [17].

This analysis assumes a recovery using a heat pump that then supplies the heat at a higher temperature, which would be capable of generating new hot water. As illustrated above, the heat supplied from the system is independent of, and can be greater than, the actual domestic hot water heating demand. Thus, this excess heat would have to be utilized by another system or deposited in a storage system for use on a later day or in a subsequent season [14].

In the periods of many uses, there is the potential that heat is not regenerated quickly enough. This will require adequate sizing of the system hot water supply, as well as wastewater recovery tank. For the 4-bedroom dataset, a cylindrical recovery tank 1.4 m wide by 1 m high eliminates all overflow events. But this was for a smaller heat transfer coefficient, which leads to a longer recovery time for each wastewater heat recovery event, and more likelihood of overflow events. As previously mentioned, the heat transfer coefficient is the most difficult variable to predict and depends heavily on the design. It is also influenced by the surface area and geometry of the tank so by observing its influence on the performance we have a proxy into the potential range of performance of the system. Figure 31 demonstrates that a reasonable performance can be expected across the range of expected heat transfer coefficients for the tank system, in this case for the 4 Bedroom dataset.

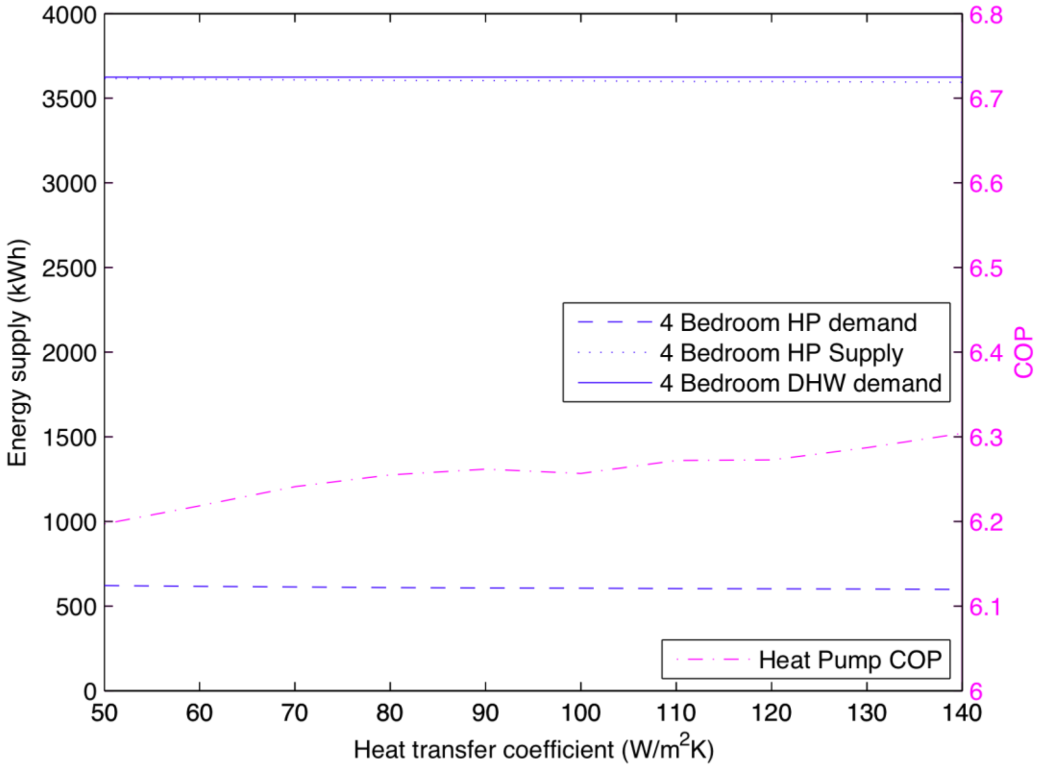

Figure 31: Heat transfer coefficient influence. Plot showing the change in the heat pump (HP) energy demand and the supplied heat compared to the constant hot water demand for a residence. In this case the 4 Bedroom dataset is plotted and an emptying temperature of 23 °C is selected so that a similar heat output to the hot water demand can be observed.

These results show that there is great potential for very effective recovery of wastewater heat made possible by extracting it at a higher temperature with a heat pump. In operation, the results will vary according to the details of system construction and heat transfer dynamics that cannot be predicted. Still, across the range of realistic overall heat transfer rates, a stable operation with high performance is observed in Figure 31. More importantly, the realistic datasets and modeled operation demonstrate the potential for a performance is not possible from modern hot water production systems.

A realization of this independent system could be envisioned for a centralized installation where the heat pump recovery supply provides heating for multiple demands. In this model, all hot water sources (shower, bath, sink, dish, and clothes) were used as inputs to simulate a larger installation. The heat pump could be part of a multistage system that also provides the base-level space heating, and if reversible, the cooling as well.

Recovery Model Connected to DHW Demand

The model for the system that directly supplied the recovered heat to regenerate the hot water supply tank using the integrated heat pump had an average annual COP of 6.7, 6.6, and 6.5 for the 2, 3, and 4 bedroom residence datasets respectively. The hot water heating demand for the closed system including only the typical bathroom fixtures of showers, baths, and clothes washing was 1700, 2100, and 2400 kWh/year respectively. In this case the heat provided by the heat pump is modeled to match these heating demand numbers. This demand was provided with a heat pump that demanded only 280, 350, and 410 kWh/year respectively. Even in cloudy Zurich, this demand could be met by less than 1 m2 of PV, and for the COP values above, if the PV has an efficiency of greater than 15%, more than 100% of the incoming solar energy can again be supplied as heat.

The closed model represents the potential scenario where the recovery tank and heat pump are built as one unit that includes the hot water supply, and they are installed within a single bathroom unit or set of stacked bathroom units in one residence. The recovery system then serves as the principle supply system for the hot water. In the model, the system recovers heat from the wastewater until the hot water supply is regenerated, thus eliminating the arbitrary emptying temperature used in the previous model.

The results were determined by first analyzing the necessary tank sizes for optimal operation. The recovery tank was sized to maximize the performance of the heat pump. This was done assuming a conservative heat transfer coefficient of 70 W/m2K. An optimal size of about 400 L was determined with the cylindrical tank diameter of 0.6 m and height of 1.5 m, as shown in Figure 32.

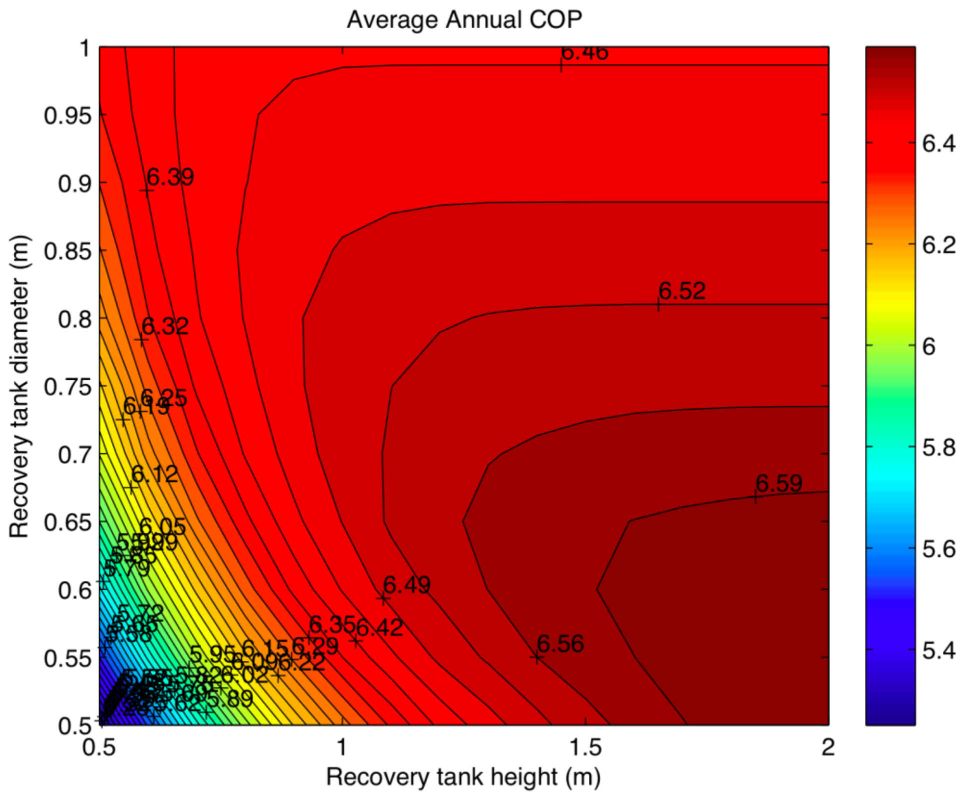

Figure 32: Contour plot of COP for tank diameter and height. The 4 Bedroom dataset is displayed to check the largest total input. The optimal operation is found around 0.6 m in diameter and 1.5 m in height, leading to a tank of about 400 L.

Next the hot water supply tank was sized to minimize the events when the hot water tank is used up, because in this case we are modeling the system to provide the hot water supply as well. Figure 33 shows the number of times per year that the supply tank of hot water runs out of water. A tank of about 400- 500L was found adequate to minimize these events to less than 10 per year for 2, 3 and 4 bedroom datasets.

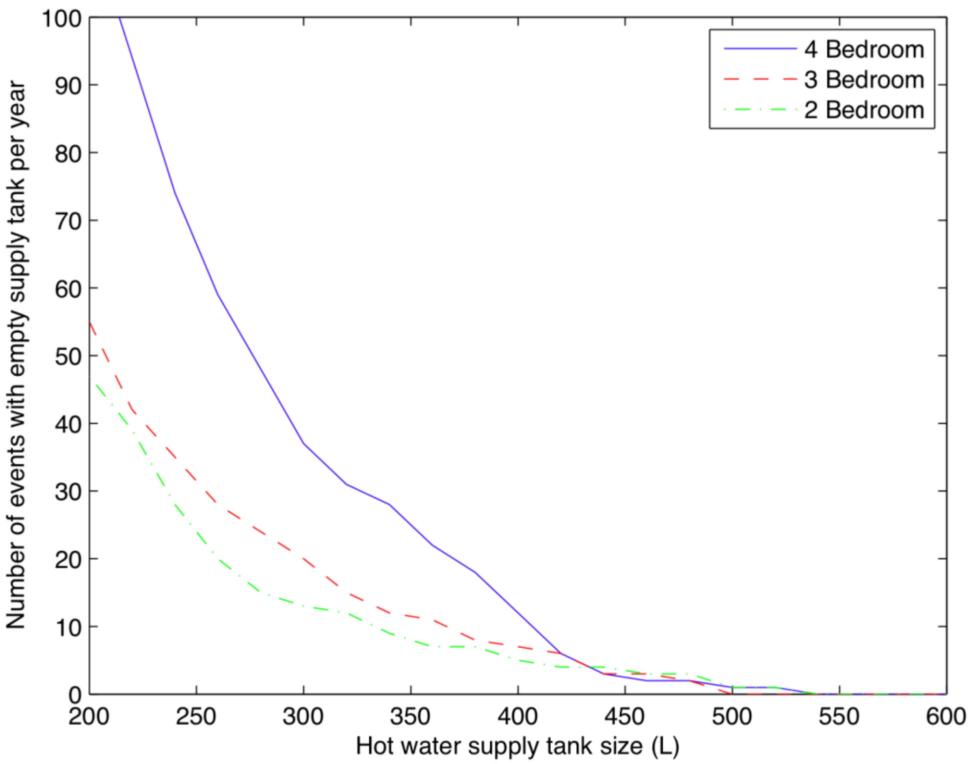

Figure 33: Adequacy of supply recovery. Plot of the number of times per year that the hot water storage tank runs out of water. At about 400 L the number of empty tank events drops below 10, and at about 500 L there are no more empty events.

Again, in this case it is interesting to observe the performance across different heat transfer characteristics so we vary the heat transfer coefficient and observe the performance change. As mentioned, the heat demand and subsequent recovery is fixed for this model, so Figure 34 shows the dependency of the heat pump work and COP on heat transfer performance. This was done for the optimized tank dimensions.

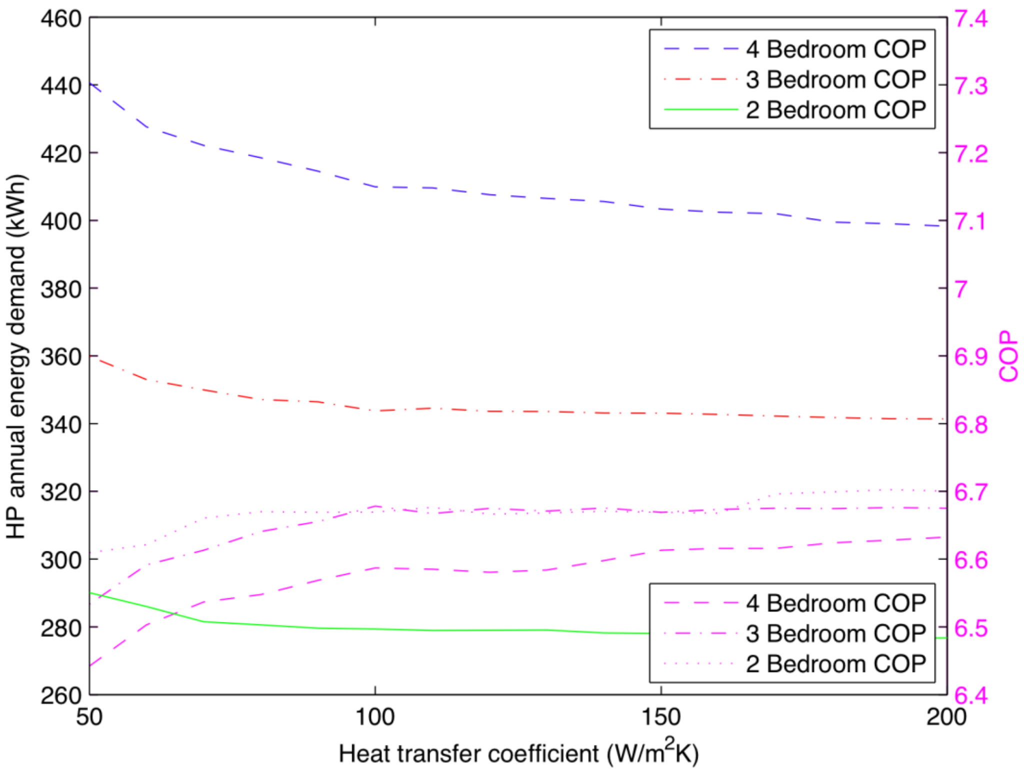

Figure 34: Heat transfer coefficient dependency for direct recovery. The change in performance of as the heat transfer coefficient is changed for the system. The heat pump annual demand and the annual average COP are plotted.

There is not a significant change in performance for varying heat transfer coefficients. The heat pump work is reduced by about 3-4% as the heat transfer is increased, caused by a slight increase in the average COP, but is more variable overall. Overall, the variation is small and so the expected performance can again be assumed to be possible across the likely variations in heat transfer of a real system in operation.

Finally, one of the last important aspects of the system operation is the relative time frame of operation of the system when supplying hot water. The average time to recover the heat from the wastewater and restore the heat supply tank to a full state is on the order of 1.5-3 hours depending on the heat transfer coefficients. This is clearly a limiting factor, and it is also a reason why the tanks need to have relatively large sizes to avoid the scenario where there is no hot water left in the supply. For this reason, it would probably be necessary to increase the power of the heat pump supply in the case when the demand runs low. This could be achieved by increasing the temperature difference between the evaporator and the recovery supply. Assuming a programmable control is used, this could be easily added to the logic. Nevertheless, although the tank sizes are large, they are not infeasible, and can achieve an acceptable performance.

Finally, we should discuss the potential implementation and the economics of such a system. The system certainly adds complexity as compared to typical hot water heating systems today, and the cost of these new components would be higher. Nevertheless, as previously mentioned, with the integration of our heat pump into other building services where we also minimize the temperature-lift [5,6], the total cost comes down, especially relative to the overall benefits achieved for the entire integrated building operation. In practice, a small system was realized in a zero energy building in Ireland [20] based on the results of a previous study [9], and a public-private partnership supported by the Swiss government was established between one of the largest sanitary firms in Europe and the ETH Zurich to bring the system to market, but was unfortunately stopped in the wake of the financial crisis. Still, further collaboration for future prototypes are under consideration and we hope more building system designers and companies consider the potential of bringing such a concept to market.

3.5.4 Conclusion

The use of wastewater heat as a source for heating systems is not often considered. It has been previously studied and implemented, but the value of the higher temperature recovery has not been exploited, and is available only close to the point of use. We have shown that there is great potential in higher temperature extraction when the recovery is combined with a low exergy system that incorporates a high performance, low temperature-lift heat pump.

Two scenarios have been studied. One for the highly integrated case where the total recovery was evaluated for all hot water sources in the building and for a unconstrained potential storage or usage for the heat supplied by the recovery. In this scenario a COP of above 6 can be maintained when the wastewater is cooled to 20 °C. The second scenario matched the heat recovered to the actual demand for hot water heating. In this case a stand-alone system can be imagined where the heat pump and recovery tank are part of an integrated domestic hot water supply system, and a COP of greater than 6.5 was maintained for all residence datasets. In both scenarios the total electrical energy demand for the heat pump operation was well below 200 kWh/year per number of bedrooms in the household. For the 4 bedroom household the, bathroom hot water heating demand of 2400 kWh/year was met with just 400 kWh/year of energy input. These low electrical energy inputs make the integration and supply by photovoltaics more feasible.

The decentralized extraction of wastewater heat on a per residence basis provides a new opportunity to achieve hot water production performance levels above what has previously been possible. Considering the increasing fraction of total building energy demand that hot water now creates as buildings are made more efficient, it is essential that we begin to focus on reducing this demand along with the space heating and cooling demands that are presently the primary focus. By looking at the system as a whole and integrating these new high performance technologies, there is still great potential for increased efficiency, and reduced demand on fossil fuels and CO2 emissions.

3.6 Market and product potential of concept

One of the initial planned outcomes of the wastewater heat recovery project was an extension into industry to initiate the creation of a product for the market. A public-private partnership project was setup between the ETH Zurich and Geberit AG. The idea was that the theoretical analysis in the Annex 49 project could provide the groundwork to move toward a pilot project with Geberit and eventually to a product. The pilot project would have been an installation in the B35 new construction project being developed in Zurich [31]. A KTI grant for project application was developed throughout 2007 and was accepted by the Swiss government in 2008. Unfortunately, Geberit decided to withdrawal from the project when internal shifts in priority made them unwilling to fullfil their side of the KTI grant for the financial commitment to develop the product. Nevertheless, the concept was actually taken on in a zero net energy home that was built in Ireland and highlighted on an Irish national television program about home building [32].

4 Other Contributions: Software, tools, pilots and other new technologies

The Swiss participants in the Annex 49 were also invovled in other projects that during the course of the Annex provided beneficial contributions as well. A Cooling Retrofit Guide was developed as a part of another SFEO project [33] lead by Basler and Hofmann, which was presented to the Annex collaborators. It presented a simple tool to encourage installation of better cooling systems, which also followed the principals of low exergy design. Also, another project that was separately supported by the BfE, but proved beneficial in discussions in the Annex 49 was the Design Performance Viewer. This is a piece of software that incorporates energy, and more importantly here, exergy calculations into a three-dimensional building information modeling (BIM) package [34]. Finally, there were several other research projects from the ETH Zurich Building Systems group that were presented in conjunction with the first Annex 49 conference in Heerlen. These included the DPV tool [34], research into a new façade system [35], a distributed pumping system [36], low temperature-lift heat pump district heating systems [37], and a study on the combination of LowEx concepts into Architecture [38]. Professor Leibundgut also contributed a paper and a presentation to the final Annex 49 Conference in Munich describing how low exergy technology can be incorporated into a real building project [39].

The main deliverables along with these contributions along with others that are part of the B35 and HPZ projects [31] were presented at the LowEx Building Symposium organized by the ETH Zurich Building Systems Group on 26.Nov, 2010 as part of a final dissemination event for the Swiss participation in the Annex 49 supported by the SFOE. Presentations were given at the HPZ and at the construction site of the B35 as shown in Figure 35.

Figure 35: Hansjürg Leibundgut presents the B35 project inside the renovated water reservoir within the building under construction at the LowEx Building Symposium organized for the conclusion of the Annex 49 to disseminate low exergy theory and technology in Switzerland.

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Appendix 1

Input parameters for the calculated SEPE examples.

System 1

Component	Energy carrier	Power input [W]	Mass flow [kg/s]	Pressure loss / rise [Pa]
Fan	Air	150	5	400
Adiabatic saturator	Air	-	5	-200
Heat exchanger 1 primary side (outdoor air)	Air	-	5	-200
Heat exchanger 1 secondary side (cooling water chiller)	Water	-	2.7	-6000
Generation Pump 1	Water	150	2.7	7000
Generation Pipe 1	Water	-	2.7	-1500
Generation Pipe 2	Water	-	2.7	-1500
Chiller primary side	Water	7600	2.7	-4000
Chiller secondary side	Water	-	1.8	-4000
Generation Pipe 3	Water	-	1.8	-1500
Generation Pump 2	Water	100	1.8	10000
Heat exchanger 2 primary side	Water	-	1.8	-3000
Heat exchanger 2 secondary side	Water	-	2.1	-3000
Generation Pipe 4	Water	-	1.8	-1500
Distribution pipe 1	Water	-	2.1	-1500
Distribution pump	Water	200	2.1	21000
Floor cooling	Water	-	2.1	-15000
Distribution pipe 2	Water	-	2.1	-1500

System 2

Component	Energy carrier	Power input [W]	Mass flow [kg/s]	Pressure loss / rise [Pa]
Fan	Air	150	5	400
Adiabatic saturator	Air	-	5	-200
Heat exchanger 1 primary side (outdoor air)	Air	-	5	-200
Heat exchanger 1 secondary side (cooling water chiller)	Water	-	2.5	-6000
Generation Pump 1	Water	150	2.5	7000
Generation Pipe 1	Water	-	2.5	-1500
Generation Pipe 2	Water	-	2.5	-1500
Chiller primary side	Water	3900	2.5	-4000
Chiller secondary side	Water	-	2.1	-4000
Distribution pipe 1	Water	-	2.1	-1500
Distribution pump	Water	200	2.1	22000
Floor cooling	Water	-	2.1	-15000
Distribution pipe 2	Water	-	2.1	-1500

System 3

Component	Energy carrier	Power input [W]	Mass flow [kg/s]	Pressure loss / rise [Pa]
Fan	Air	150	5	400
Adiabatic saturator	Air	-	5	-200
Heat exchanger 1 primary side (outdoor air)	Air	-	5	-200
Heat exchanger 1 secondary side (cooling water chiller)	Water	-	2.7	-6000
Generation Pump 1	Water	100	2.7	7000
Generation Pipe 1	Water	-	2.7	-1500
Generation Pipe 2	Water	-	2.7	-1500
Chiller primary side	Water	10500	2.7	-4000
Chiller secondary side	Water	-	1.2	-4000
Generation Pipe 3	Water	-	1.2	-1500
Generation Pump 2	Water	100	1.2	10000
Heat exchanger 2 primary side (chiller)	Water	-	1.2	-3000
Heat exchanger 2 secondary side (supply air)	Air	-	4	-300
Generation Pipe 4	Water	-	1.2	-1500
Heat exchanger 3 primary side (exhaust air)	Air	-	4	-300
Heat exchanger 3 secondary side (outdoor air)	Air	-	4	-300
Fan (supply air)	Air	200	4	500
Fan (exhaust air)	Air	200	4	400
Air inlet / outlet	Air	-	4	-50

Appendix 2

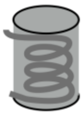
Free convection tank analysis report to Geberit.

Tank Performance Report

14.05.2009

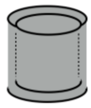
by Forrest Meggers, ETH Zurich

Background



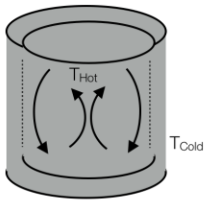
- The original analysis of the tank assumed a simple spiral heat exchanger in a constant temperature fluid.
- This was used for the "Exergy Optimization of WRG" and the "WRG System Report" documents.
- The potential problem from fowling as found in FEKA systems led to a new concept for heat exchange.

New Tank Design

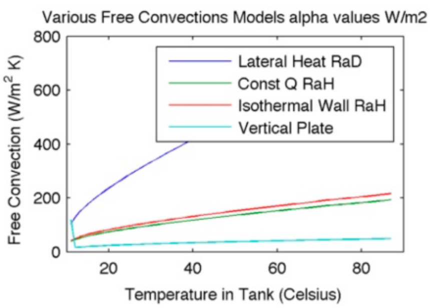


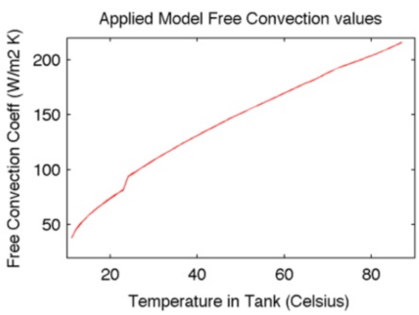
- A system with simple smooth interior walls was designed, which would be much easier to clean/maintain.
- The heat exchange takes place via a shell around the outside of the tank.
- This required a new more complicated model for the heat exchange process involving free convection.

Free Convection



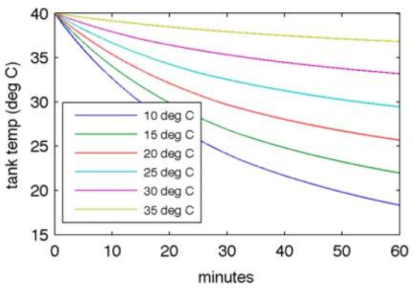
- In the case of the spiral pipe a heat exchanger fluid was assumed to change temperature.
  - In the shell we assume a constant temperature fluid (this would be the case for a direct connection to the heat pump as well as for a high enough flow rate.
  - The flow rate was used previously to control the exergy destruction but is ignored in this case.
- Several free convection models were used from Martynenko and Khramtsov's reference book, *Free Convective Heat Transfer* in order to obtain a heat transfer coefficient.
  - The resulting heat transfer coefficients are plotted below for various tank temperatures
    - Assumptions: Tank size: 0.5x0.5 cylinder and cooling fluid temperature of 10°C
    - The models produced a range of outputs and 2 seemed to be consistent
    - The Isothermal Wall model was applied for the analysis and is also plotted below
    - For a 20-30°C temperature difference this gives a heat transfer coefficient of about 100 W/m²K
      - **This is a good value and would provide adequate heat exchange for tank operation**

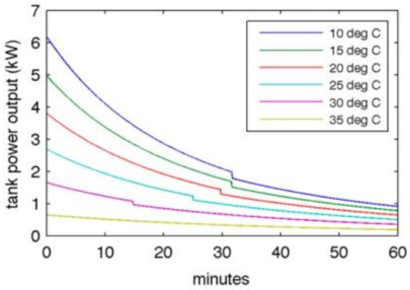




Tank Operation

- The heat transfer coefficient from the free convection analysis allowed the tank operation to be observed
- The power output and the temperature of the tank is plotted below for one hour of 40°C wastewater input
  - Assumptions: 0.5x0.5m (100L) tank and cooling fluid at 10 - 35°C (low temperature lift heat pump)
  - The total energy recovered over the hour is ~1 kWh with a max power output of 2.5 kW
    - A typical shower needs about ~4 kWh so a heat pump with COP > 4 can recover and replace the hot water
    - **The tank operates with sufficient energy recovery for the hot water system**





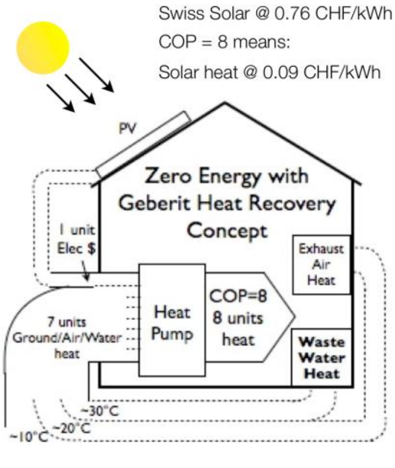
- The table to the right shows the power demand
  - As the source temp increases the smaller power is available (above right)
  - **Still there is sufficient power to run the heat pump described below**

Power for hot water production of 100 L 55°C					
Time to production	Heat demand (kW)	HP Elec (kW) COP=5.5	HP Elec (kW) COP=6.6	HP Elec (kW) COP=8	HP Elec (kW) COP=15
0.5 hr	9.4	1.7	1.4	1.2	0.6

- **Fowling:** Any fowling of the inner surface greater than **1 mm** could have a significant impact on power output
  - Assumption: 0.1-0.4 W/mK thermal conductivity for a typical organic fowling material

LowEx Heat Pump System Integration

- The results above are for a variety of recovery temperatures. Pink shows the 30°C Operation described in the this concept ->
  - The following discussion is based on a 30°C recovery
- If the Heat pump operates with a exergetic efficiency of 0.5 the COP for producing 60°C water would be 5.5 for 30°C source
- Recent research from Prof Beat Wellig, HSLU in Horw produced a low temperature lift heat pump with exergetic efficiency of 0.6
  - This leads to a COP = 6.6
- For the LowEx building concept being applied to in the B35 project hot water will be produced at the usage temperature of around 40°C and only augmented for small uses
  - Even with a exergetic efficiency of 0.5 the COP is better
    - **50°C gives a COP of 8 as shown ->**
    - **40°C gives a COP of 15[1]!!**



[1] No machine to produce a 10 degree temperature lift is readily available yet

2/2