Doctoral Thesis

Exergy analysis of building systems
improved exergetic performance through systems integration

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EXERGY ANALYSIS OF BUILDING SYSTEMS:
IMPROVED EXERGETIC PERFORMANCE THROUGH SYSTEMS INTEGRATION

A dissertation submitted to
ETH ZURICH

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Doctor of Sciences

presented by
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2011
“There is no energy crisis, only a crisis of ignorance”
--Buckminster Fuller
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Kurzfassung


Im Vergleich zu anderen Systemen, wie z.B. Verbrennungsmotoren, wird in einem Gebäude-System eine relativ niedrige Temperatur benötigt um das Raumklima aufrecht zu erhalten. Das Ziel ist daher die Exergie zu minimieren, die erforderlich ist, um dieses Klima aufrecht zu halten. Dies kann durch Niedrigexergie-Systeme durchgeführt werden, die nicht nur den Energieeinsatz minimieren, sondern auch die Temperaturgradienten reduzieren, welche die Exergievernichtung im System verursachen.

**Summary**

Buildings play a role in nearly every facet of daily life, yet the great impact of buildings on society is often taken for granted. The energy demand of their role cannot be taken for granted any longer. When all aspects of the building sector are considered, buildings are responsible for more than half of greenhouse gas emissions, demanding 2/3 of global electricity generation. Significant mitigation of climate change is possible through improvements in the building sector.

The objective of this research is to evaluate the use of the concept of exergy to instigate some of the necessary improvements in the building sector. Novel concepts are surveyed and analyzed, and new design perspectives are explored and implemented. The role of these results is also considered in the broader context for buildings and for the global changes that need to occur.

Exergy is a concept that combines the basic concept of energy from the 1st Law of Thermodynamics with the concept of entropy from the 2nd Law of Thermodynamics. It allows calculation of the real limitations of thermodynamic cycles such as heat engines, thermal plants, and heat pumps to utilize or generate work. Limitations are quantified by the inherent value of various forms of energy. In the case of buildings, heat is of the most interest, and heat is very relevant for exergy analysis. Exergy quantifies the increased value in a quantity of energy stored as heat based on its temperature. A small volume of high temperature heat can contain the same amount of energy as a large volume of heat at a lower temperature, but the high temperature heat source contains more exergy. Exergy is used to define the potential of a source of energy at a certain temperature to interact with its surroundings at a different temperature to provide useful output. The larger the temperature difference the larger the exergy demand, which may not be accurately quantified by a simple energy balance alone.

For a building system, the room climate is maintained at a relatively low temperature as compared to other heat systems like engines. The goal is to minimize the exergy needed to maintain this climate, and this can be done through low exergy systems that minimize not only the energy input, but also the temperature gradients that cause exergy destruction in the system.

A further background of this project and exergy and buildings is provided followed by a series of papers. The first set deal with the analysis and modeling of wastewater heat recovery using exergy analysis and then a second dealing with the design and evaluation of a low exergy active insulation system. The discussion and consideration for how the concepts of exergy and its counterpart, anergy, can be utilized in building is provided in another paper. Finally the broader application of entire low exergy systems with low temperature-lift heat pumps is presented followed by an even broader analysis of the necessary changes in the building sector including the role of low exergy technologies and concepts.
Acknowledgements

First acknowledgements go to my advisor and mentor, Prof Dr. Hansjürg Leibundgut. He not only provided the inspiration for the ideas and concepts in this research, but he was also an inspirational person to work with, skilfully navigating the channels of technological development to turn theory, ideas and concepts into realized projects, systems and technology with a direct impact on society. I also thank him for his patience and for the freedom he allowed in my research, and for giving me six months to learn German supporting my extra research into Swiss customs, topography, and food. Thanks also to my co-advisor, Prof. Dr. Konstantinos Boulouchos, for taking time to contribute to the initial development in my first examination, and now in the finalization of work of my thesis.

Another huge thanks goes out to my family. Without the support of my wife, Georgette, I would never have completed this work. Even while she was writing her own PhD thesis, being 7 months pregnant, and working in Bern, she still helped me whenever the going got tough. As always in my life, my parents Jane and Mike gave me all the support I could ever ask for. Thanks for being a huge support, and telling me if what I’m doing makes any sense. In the end my mom, Jane, will have probably read this thesis more than anyone, helping me find grammar mistakes and confusing sentences.

I also owe a large debt of gratitude to all my friends who have worked with me in the Buildings Systems Group. Thanks to everyone for putting up with my German. Thanks to Luca for being a great teammate and partner in all our projects and providing the needed anergetic debate. Thanks to Arno and Frank for supporting my work on exergy and letting me freely express my frustration with architects. Thanks to Marcel for understanding games with anergy, Christoph for helping to free my research, Volker for showing me how to roll out nice graphics, Marc for providing his mechanical support of the team, Matthias for helping the flow of my work, Philippe for balancing the ideas against new obstacles, Daren for sniffing out any major mistakes I might be making, and last but not least to Valère for all the administrative support.

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I would like to officially dedicate this work to:

Ms. Mary Meggers and Dr. Eugene Lister

Thanks for the knowledge and wisdom they have inspired in me and given the world.
Publications

2011/12

Papers


Publications


2010

Book Chapters


Papers


Reports


Presentations

Forrest Meggers. "Professionals". Contribution to the final presentation, "Reduce CO2: With technology to zero emissiosn" at the Holcim Forum, Mexico City. March, 2010


2009

Papers


Presentations


- Presentation at Universidad Andres Bello, Valparaiso, Chile, Sept 7, 2009.
- Presentation at Universidad Andres Bello, Santiago, Chile. Sept 9, 2009.


Publications


2008

Papers


Presentations


Publications

2007
Papers
Included Publications

CHAPTER 2: Wastewater Heat Recovery

AIVC:

PLEA:

CISBAT

Energy and Buildings

CHAPTER 3: Active Low Exergy Geothermal Insulation System
in submission
Forrest Meggers, Luca Baldini and Hansjürg Leibundgut. An innovative use of renewable ground heat in a building insulation system. In submission 2012.

CISBAT

CHAPTER 4: Exergy Concept for Buildings

International Journal of Exergy (in press)
CHAPTER 5: Integrated Low Exergy Systems

Clima 2010

Energy (in press)

CHAPTER 6: Reduce CO2 to Zero Emissions

Sustainable Cities and Society
1 Introduction and Background

1.1 Motivation

The energy demand of buildings has both grown in quantity and in importance over the last century. Historically electricity and heating fuel were cheap and a rather insignificant cost for buildings. The advent of air conditioning, a vast expansion in technologies, and an increase in average size of buildings have led to a dramatic increase in energy demand. Estimates now put greenhouse gas emissions from operation, construction, and maintenance of buildings at over half the world total [1]. Improvements in the building sector have become critical for the mitigation of climate change. The resources consumed by buildings can be categorized into two areas: materials and energy. With buildings generating half of global waste and having huge indirect demands for material resources [2], use of material must be optimized. Finally, buildings demand two-thirds of global electricity production [2], and improvement in building systems can have a huge impact in this area. Combined with the rise in price of energy and environmental costs of energy production, the primary focus of this thesis will be on the area of building energy demand and how it can be reduced using exergy analysis in the development of novel integrated systems.

Clearly, energy demand for buildings is reliant on the building services that demand energy. These are dominated by space heating and cooling, hot water production, and electricity for lighting and appliances. When analysis was first employed to reduce building energy demand, the obvious approach was to look at each system and make it use less energy. The equipment that supplied building services where energy was demanded, such as furnaces and air conditioners, were designed by engineers to be more efficient. Also, in order to reduce the demand for the service itself, designers tried to minimize energy losses through strategies such as improving insulation and optimizing window positions to capture energy. These processes continue today, but many times they are restrained by individual component costs and by frequent disconnects between engineers and designers. Also, there is a limit to how energy efficient each individual component can become. There comes a time when just the amount of energy used cannot by itself remain the sole objective. In order to continue making significant reductions in energy demand these restraints must be removed. Systems that integrate the engineering and the design are necessary, and consideration has to be taken for not just the raw quantity of energy used but also its quality and its potential usefulness, which is accounted for in the concept of exergy.

The motivation behind this project is to achieve both more integration in building systems, as well as to analyze both the quantity and quality of the energy used through exergy analysis. Exergy captures the loss in the ability of a quantity of energy to perform useful work. It quantifies the energy transfer in any process, and it includes a term that quantifies a loss in quality or usefulness of the energy after the transfer. These are losses that are often not accounted for in building analyses, and it is therefore interesting to investigate the application of the concept of exergy for designing and evaluating better building systems.

The investigation of exergy and buildings is the central theme of this thesis, and it will be presented in a series of publications along with the initial chapter, which will provide background and context to the various areas of research. Exergy consumption of water heating and the evaluation of exergy recovery from wastewater were the first primary
research topics. Several models were developed in the analysis of wastewater heat recovery, providing the results given in the four papers in Chapter 2. In Chapter 3, two papers present the potential of a counterintuitive system that supplies heat to the outside of a building shell. The system uses freely available renewable ground heat to reduce the transmission losses through the building façade. Chapter 4 presents a paper that explores the methodology of exergy analysis in the context of building system design and optimization is considered. The integration of these building services into a single system is studied in Chapter 5, which explores the benefit of system integration when using low exergy concepts combined with a heat pump. Finally Chapter 6 concludes with a broad review of significant changes that can be implemented in the buildings sector to reduce its large CO₂ emissions.

1.2 Research Objective

The research strives to evaluate the use of the concept of exergy based on the principles of the 2nd Law of Thermodynamics to improve the performance of buildings. The concept of exergy is analogous to energy except that exergy incorporates a factor that evaluates the actual potential of an amount of energy to perform useful work using thermodynamic cycles that are limited by the 2nd Law. This potential is especially relevant when evaluating heat transfer. Therefore the use of exergy analysis can provide new insight into how to best design and combine building systems for optimal performance. The assessment of these new low exergy developments is the core objective of the research.

The underlying supporting objectives of this research are many. The large impact of the building sector on the environment has been made clear, and increasing the performance of building systems to reduce this impact is crucial. Reducing CO₂ emissions from building operation plays a significant role in the pursuit of this research. The development of new innovations is also a driving force behind the work being done. Finally, an expansion in the accessibility of low exergy concepts and techniques to designers plays a role in this research endeavor.

The research includes analysis of specific case studies of low exergy system development, consideration of the utilization of exergy for buildings, and observation of the overall potential of low exergy systems in buildings. It provides some level of fundamental assessment of low exergy systems, and contributes to the supporting objectives of implementation as well.

1.3 Project History

This project was initiated through discussions that took place over the summer of 2006 and into 2007. The common interest in finding solutions to reduce the energy demand of buildings evolved into this doctoral research on low exergy systems for buildings. A bachelor degree in mechanical engineering was well suited to the research in the field of exergy, and a master degree in environmental engineering with a thesis on building services provided a good framework for the exploration of reducing the environmental burden of buildings.

The research initially focused on the review of potential applications of exergy in building systems. That led to the primary research focus being developed in 2007 with Prof. Leibundgut on the recovery of heat from wastewater for the optimal generation of hot water using a heat pump. The project was initially driven by a public-private partnership that would support the research into the operation of a wastewater heat recovery system,
and that would lead to the development of a new product for the market. A CTI (KTI) grant from the Swiss federal government was accepted, but the industry partner withdrew participation before the official project could begin. Nevertheless, the theoretical aspects of the research were developed and several conference papers and a journal paper in *Energy and Buildings* were generated as a result. As a result of one conference paper, a prototype system was developed and built in Ireland, and the concept has been featured in an industry magazine.

Along with wastewater heat recovery a second applied research concept was developed in collaboration with Dr. Luca Baldini and Prof. Leibundgut. This was a system that was developed as a result, not of a specific exergy analysis on the building system, but rather from application of exergetic principles in the development of building systems. The system utilizes ground heat in an external layer of a building façade to reduce the temperature gradient across the wall during cold conditions. It reduces the heat transmission, and diminishes the heat demand of the building. The idea of finding a direct use for the freely available heat in the ground is a result of consideration for the limitations of exergetic performance and the concept of an anergy source. A model was built and the static performance and design of the system was evaluated as well as the dynamic seasonal operation. The theoretical analysis and results have been submitted for publication in the journal *Renewable Energy*, and the application and evaluation of the performance of such novel system for a pilot project and its energy performance mandate were presented at a conference.

The analysis of these systems and the basic research into low exergy systems for buildings was supported through the participation in the International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems (ECBCS) Annex 49, “Low Exergy Systems for High Performance Buildings and Communities.” The Swiss participation was led by Forrest Meggers and provided an international framework for the discussion and evaluation of design concepts and analysis methods. It also led to the further investigation into the general idea of how the concept of exergy can be applied to buildings. The project provided the impetus for the exploratory paper into the utilization of the concept of exergy and anergy for buildings, which was presented at a conference and has been submitted for publication in the *International Journal of Exergy*. One of the major obstacles of exergy analysis for building systems is the definition of a reference state, and a conceptual methodology is described that argues how this reference state can be viewed in order to generate a better understanding of exergy and anergy in the context of buildings. This is supported by the success with which the conceptual framework has been implemented in Zurich within the architecture field, allowing designers who are less familiar with thermodynamics come to grasp the fundamental design implications and benefits of low exergy systems.

The experience in the Annex 49 and the further expansion of the Building Systems group led to development of a wider range of technologies and an expansion of the potential combined performance. In conjunction with recent developments in the performance of low temperature-lift heat pumps [3, 4], which are central to a low exergy system, the performance of integrated low exergy systems was evaluated in several conference papers, one of which is submitted for publication to the journal *Energy*. The expanded approach led to reincorporation of the initial fundamental research into the performance of wastewater heat recovery into a larger context that provides a better general understanding of integrated low exergy systems for architects and designers. It demonstrated a large potential of low exergy systems, albeit not yet realized in the building market, but
nevertheless providing a large incentive to explore the potential of such systems. It also provided an excellent illustration of how active systems can be developed that utilize low exergy concepts, and provide equal performance of passive systems with much less material demand.

These developments coincided with the planning and construction process of the B35 building and HPZ buildings, which are highlighted in the ViaGialla collaboration that is supported by the building systems group. The projects have provided excellent resources for the demonstration and implementation of the low exergy systems under development and being presented in this research.

Finally, the research culminated in a project that brought the concepts and ideas that had been developed into a much broader context of making buildings more sustainable. The focal point of this development was the idea of reducing building CO2 emissions to zero using technology and concepts that are readily understood. It was done as a part of a unique international collaboration organized by Prof. Leibundgut for the 2010 Holcim Forum for Sustainable Construction, in which researchers from around the globe worked together to generate an analysis of the potential concepts that could bring buildings to zero emissions. A paper was coordinated by Forrest Meggers and submitted to the journal *Environmental Science and Technology* that consolidated the work of the group, and demonstrates how exergy analysis and low exergy systems fit in with other important aspects of the building sector such as material demand, renewable energy integration, and construction and demolition methods.

### 1.4 Literature Review

#### 1.4.1 Exergy and Buildings

Besides the broad technical and thermodynamic aspects of exergy analysis of building systems, there is a large array of work that is directly related to this research. Research into low exergy systems for buildings has been expanded by work over the last ten years in the IEA (International Energy Agency) ECBCS (Energy Conservation in Buildings and Community Systems). It came first from the IEA ECBCS Annex 37, “Low Exergy Systems for Heating and Cooling Buildings,” and subsequently from the Annex 49, “Low Exergy Systems for High Performance Buildings and Communities,” in which this project played a role. The Annex 37 resulted in the creation of a LowEx website to support the network of low exergy building researchers [5]. Here the materials from the Annex can be downloaded, including a technical introduction to exergy and building systems [6] as well as the full guidebook that resulted from the Annex 37 [7]. Annex 49 maintains a website where material and information can be obtained, and the Annex 49 also generated an extensive guidebook [8]. Both Annexes generated and supported the use of analysis tools that facilitate the evaluation of buildings using exergy [9, 10], and these tools are also documented online along with other material on low exergy buildings [5, 8].

Various national and international projects have also focused on exergy analysis of buildings or building components. A European COST Action was setup to support the development of low exergy concepts in the European context [11]. A technical group of ASHRAE, Technical Group 1, was created to consider exergy in the US [12].

Aspects of available energy from the second law of thermodynamics have been applied to the building sector by Gaggioli in 1981, which describes the potential benefit of addressing second law efficiencies[13]. Although it incorporated the term exergy and provided excellent
analysis, the work was not recognized and the use of exergy for buildings did not begin to expand until some of the first papers appeared from Shukuya in Japan [14]. His ideas were eventually presented internationally in 1994 [15], explaining the exergy-entropy process of building processes via a forced air convective heater. Later Shukuya would investigate the exergy-entropy process of passive solar heating [16], and he would further discuss the extension of the second law aspects of thermodynamics into architecture and building science [17]. Shukuya demonstrated a new perspective in building analysis and helped to instigate the IEA Annexes previously mentioned, which have stimulated the growth in the field of exergy analysis of buildings.

More recent research has come out in the area of exergy and buildings, some as a direct result of work in the Annex 37 and 49. Shukuya has provided further explanations of application of exergy in the building sector for the development of better building technologies [18], and a further analysis of the exergy flows in building systems has been presented as a part of Annex 49 by Schmidt [19]. Torio and Schmidt published a rather extensive review of the research on the use of exergy analysis to increase building efficiency as well as the use of renewable energy in buildings [20]. A comprehensive review was done by Hepbasli that focused on the exergy analysis of renewable energy resource capture and utilization [21]. Simone et al and Shukuya et al have also extended the use of the concept of exergy for the evaluation of optimal comfort in buildings, which utilizes a new metric for the human body exergy. Schweiker compared occupant behavior to building exergy efficiency [22]. Torio has developed a framework for better analysis of solar energy systems for buildings using exergy [23], and Dovjak looked at a specific case study of exergy consumption patterns for space heating in a set of Slovenian buildings [24]. Also, the exact exergy characteristics of various fuel types has also been studied using exergy analysis [25]. Exergy has also been integrated into the building permit process in the canton of Geneva in Switzerland, and Favrat has presented the implementation and its significance of this expansion of exergy analysis into the realm of policy and regulation [26].

Several recent conferences have been organized that focus specifically on the use of exergy in buildings. This includes the ELCAS 2009 conference ([International Exergy, Life Cycle Analysis, and Sustainability Workshop] [27], organized as part of the European COST Action [11]. Additionally, two conferences were organized as a part of the Annex 49 [8]. These were the The Future for Sustainable Built Environments - Integrating the Low Exergy Approach [28] and The Future for Sustainable Built Environments with High Performance Energy Systems [29]. Finally a LowEx Building Symposium was held [30], which discussed many of the technologies that are presented in this thesis.

Additional doctoral research has focused on the application of exergy analysis to buildings. Wall looked at the concept of exergy related to the housing sector in Sweden in his thesis [31] and related paper [32]. More recently, Cornelissen looked at the role that exergy analysis could play in sustainable development, including the description and impact of a variety of applications for buildings, specifically considering the building life cycle [33]. Schmidt extended the use of exergy in buildings by developing and implementing a tool for low exergy design of building systems that facilitated the comparison of exergetic performance for different heating supply structures for buildings [34]. Sakulpipatsin provided an extensive review of the methodology for exergy analysis of buildings by, amongst other aspects, observing the importance of the reference environment, and also evaluating the significance of the chemical exergy in moist air when dealing with humidity [35]. Colleagues at the ETH also made advances in the application of exergy and buildings. Baldini used the concept in analysis of decentralized ventilation systems [36], and Schlueter expanded the
use of the concept into the modeling and design phase for buildings [37]. Besides these doctoral works, there is also a significant amount of research that will be coming out of other doctoral projects that were related to the Annex 49 research [38].

Many books have been published that address the concept of exergy in depth. These include the fundamentals book by Moran and Shapiro, which explains the thermodynamic basis for exergy and its implementation [39], and the more advanced thermodynamics book by Bejan that covers multiple applications of the concept [40]. Bejan specifically looked in detail at the application of the concept of entropy generation minimization [41], which is very relevant to exergy analysis. One of the first books that looked at exergy and provided the first definition of exergy as energy that can be transferred to any form was by Baehr [42]. Some of the original work on the application of exergy to systems was done by Kotas [43], when he explored the use of exergy for thermal plant optimization and described some new efficiency metrics based on exergy, as described in the Theoretical Background, section 1.5. Also described in section 1.5, the work of Brodyanski created a new perspective on the use of exergy through the idea of utilization [44]. More recently the concept of exergy has been the focus of several contemporary books, including the work by Szargut on the impact of exergy within both technical and ecological systems [45], and by Dinçer and Rosen exploring the role of exergy in sustainable development [46]. Borel and Favrat have just published a new mechanical engineering book on energy system analysis with extensive review of the use of exergy analysis [47].

1.4.2 Heat Pumps and Exergy

Research on heat pumps specifically is not the focus of this research, but the operation and performance of heat pumps plays a very central role to the research and concepts developed in this thesis. A very broad review of heat pump types and operation is provided by Goldschmidt [48]. The book by Bermeister covers the details of heat pump thermal-fluid processes [49]. Zogg did a review of the history of heat pumps and their development in Switzerland [50], and this explained the development of the many of the performance criteria for current heat pumps, the limits of which are pushed by the concepts in this thesis. An extensive evaluation of working heat pump performance in Switzerland was carried out by the Swiss Federal Office of Energy, and it showed that an air-source heat pump had an average annual COP of 2.7 and ground-source of 3.5 [51, 52]. These results leave room for improvement through concepts such as integrated low exergy systems.

A critical area of research that needed to be considered with regard to heat pumps for this thesis is the real operational potential of heat pumps in low exergy systems. In this thesis, the focus is not on the internal dynamic operation of the heat pump, but that aspect is nevertheless important to the overall performance, so it must be considered. For this reason collaboration was maintained with researchers at the Lucerne University of Applied Sciences and Arts. Researchers there led a Swiss Federal Office of Energy project that investigated the potential increase in efficiency of heat pumps through exergy analysis of the individual heat pump components [3]. The study focused on air-source heat pumps, but the analysis helped to show the potential of minimizing exergy destruction and the potential of using exergy to pinpoint areas with a large potential for improvement, which leads to better overall performance. The analysis was expanded in this work into the overall building system, except in this case the performance of the entire heat pump plays the role of a single component, and the overall building system is optimized with a primary area of focus being wastewater heat recovery. In order to argue for high performance of the heat pump in the integrated building system model, further results were used from Lucerne that demonstrate
very high heat pump COP at low operating temperature-lifts. It showed that a heat pump built with standard components and an oversized electronic expansion valve could maintain a Carnot efficiency above 0.5 at a temperature lift of 12 K, therefore having a COP of 13 for heating [4]. This work provided the basis for the potential performance of the integrated heat pump systems evaluated in this thesis.

There have been a wide variety of research papers on heat pumps as well as on energy use in buildings, but combining exergy analysis with heat pumps and building system analysis is not as common. Actually, the exergetic analysis of heat pumps has been ongoing since the 1980's including work by Leidenfrost optimizing heat pumps [53, 54], and by Wall considering the economic aspects as well [55]. There have been several case studies reporting on geothermal heat pump performance, including exergy analysis component by component of the heat pump [56, 57]. But these case studies do not look at integration into other building concepts like low temperature heating or cooling. There is a study looking specifically at the use of low temperature ground source for heat pumps but it does not incorporate a broad look at the building system as a whole [58]. Of note is an exergy analysis of large scale district heating systems, which could be of interest if the water system analyzed in this project would be applied to a district system [59]. Lohani presented a comparison of ground source heat pumps to a base case conventional fossil fuel system, which demonstrated the heat pump to have a 25% lower primary energy demand and exergy demand [60].

One more component that has been considered in the analysis of heat pump and heating systems for buildings using exergy analysis is the addition of solar exergy. Such systems have been studied in depth in Turkey, with full exergetic analysis of each component in the heat pump including the added exergy from solar heating of the ground loop of a ground source heat pump [61]. Two such potential applications have been compared in Turkey [56]. The way in which solar exergy and radiation exergy is calculated was studied in order to accurately model input from radiation sources [62, 63]. Torio presented a new methodology to evaluate the exergy value of solar inputs into building systems [23], which impacts the way solar heat pumps could be analyzed. Especially relevant to the hybrid photovoltaic system discussed as part of the integrated system described in Chapter 1 is the work by Wang describing the use of thermal energy from a photovoltaic in a heat pump system. Wang employed both a performance study and a case study where the heat is stored in the ground with an efficiency of 40% of total solar irradiation [64, 65]. Ji also showed the exact performance of a heat pump evaporator used in a photovoltaic panel to range from 64 to 87% [66]. In Further work, Kumar presented an exergy analysis of a hybrid thermal photovoltaic panel, showing that the exergetic efficiency of an active solar is 25% higher than a passive system, while the energy efficiency is at the same time 24% lower [67].

1.4.3 Domestic Hot Water and Wastewater Heat Recovery

As hot water heat demand and the recovery of potential from hot water played the first primary role in this work, a literature review of this area is also considered. The idea of using exergy analysis to study and validate a wastewater heat recovery system, as discussed in the principle research in Chapter 0, is a novel concept. Nevertheless various works have been conducted on the individual aspects and components of the system that formed a starting point and basis for the development of the research. Historically, exergy analysis of storage systems has been considered since Koefed in the 1980’s [68], and it is with this component analysis that a larger potential integrated system can be considered.
As a part of the IEA Heat Pump Programme Annex 28, a test procedure was developed for calculating the performance of heat pumps that provide both space heating and domestic hot water heating. The test mostly looked at an appropriate way to evaluate the seasonal performance of a heat pump that produced both space heating heat as well as water heat. These concepts were presented in a conference paper, a final report, and a final guidebook [69-72]. The new method for seasonal performance of an integrated heat pump systems not only described how a heat pump can be used for both systems, but could be used to validate the benefits of using heat pumps to provide heating for both systems. A full exergy analysis of the system was not included, but the benefits of such an analysis were addressed.

The IEA Heat Pump Centre also provided a study of domestic hot water heat pumps [73]. The study gave the performance and characteristics of a wide variety of heat pumps for providing hot water. The heat pumps were grouped into various types, including models that used exhaust air as a heat source, and that provided an excellent comparison for the research into wastewater heat recovery. Wang more recently presented the analysis of a multifunctional heat pump for space heating and hot water production that showed a better performance than solar thermal systems, and had a higher coefficient of performance during cold outside temperatures [74]. His work also provided an interesting comparison to the system developed in Chapter 0.

Torio presented an exergy analysis of the utilization of industrial waste heat that demonstrated how by matching the quality of the waste heat to the usage source, thus minimizing temperature differences, the exergy efficiency could be increased significantly [75]. This was interesting because it also showed, as is shown in Chapter 0, that an energy analysis alone is not able to demonstrate the added benefit shown with exergy analysis.

A primary area that needed to be researched in order to understand the potential of hot water heat recovery was the actual usage patterns of hot water in typical residences. Jordan developed a tool for hot water schedule generation and analysis at the University of Kassel [76, 77]. His concept allowed for a flexible generation of a variety of usage scenarios, but lacked substantial statistical data to support the output. In the United States, Hendron developed a more precise set of hot water events, but only for a specific set of residence sizes [78, 79]. These data sources provided a robust input to observe the energy and exergy demand and potential recovery in wastewater.

Other studies relate more closely to the topic of wastewater heat recovery. In Switzerland, the potential use of heat from the central wastewater collection canals was evaluated and implemented in heat pump systems to provide district or large scale heat supply [80, 81]. Also in Switzerland, a similarly large scale system called FEKA was implemented in large hotels and large multifamily residences, which extract heat from a centrally collected wastewater source to provide a higher temperature heat source for the heat pump system [82]. Fraefel designed and implemented his own wastewater heat recovery system in Grueningen, Switzerland in 1996, and it successfully helped provide space heating, but did not help the hot water production directly [83]. Finally, Bernier has described in two papers the potential benefit of collecting heat from a grey water system to increase performance [84, 85].
1.5 Theoretical Background

1.5.1 Energy and Entropy Background

The scientific theory of energy is clearly fundamental to any analysis of building energy demand. The aspects of energy analysis most relevant here are those relating to building operation. The principles of interest are rooted primarily in the fields of thermodynamics, fluid dynamics, and heat and mass transfer. Other fields that can also have impacts on energy demand worth mentioning include statics and dynamics, material science, topology, geology, ecology, and meteorology. These fields relate mostly to building construction and location, but nevertheless they have some influence on building operation and so are still important to consider.

This research relies primarily on the three fundamental areas: thermodynamics, heat and mass transfer, and fluid dynamics, with a main focus on thermodynamics. Thermodynamics studies the steady-state relationships of systems and how they interact with their surroundings. The first law of thermodynamics provides the basis for analysis of energy demand and is the principle behind most energy modeling for buildings. Fundamentally, it states that for any adiabatic process, one with no heat transfers, the state at the beginning and end determine the work output independent of the path the process takes [39]. This generates a standard energy balance used to determine the heat flows and energy demand in a building. This research strives to go beyond the standard conservation of energy for buildings by exploring the application of the second law of thermodynamics to building systems. The second law of thermodynamics explains the natural direction of flows of heat from hot to cold, and defines the limits that this directionality places on the potential of thermodynamic processes [39, 40].

Historically, the first and second laws of thermodynamics evolved simultaneously. But more than a decade before either existed, Sadi Carnot (1796-1832) was already experimenting with the limitations placed on the engine output by the temperature inputs, which would lead to the development of his seminal work in 1824, *Réflexions sur la puissance motrice du feu* (Reflections on the Motive Power of Fire) [86]. His work explained for the first time a theoretical limit to the maximum output of an engine based only on its operating temperatures. Although not expressed in precise equations and derivations, Carnot’s formulation had great impact, and eventually was recognized as one of the first expressions of the second law of thermodynamics. His work had a major influence on the development of subsequent machines. Eventually the 1840’s brought more mathematical derivations and proofs in the field of thermodynamics.

The first law of thermodynamics precisely defined the conservation of energy. The equivalence of heat and work was shown by Julius Robert von Mayer (1814-1878) in 1842 [87], and during the years 1840-1845 [88-90], James Prescott Joule (1818-1889) experimentally proved this equivalence, which now forms the basis for determining the amount and how to supply all buildings with heat and comfort. The first exact definition of the first law of thermodynamics was given by Rudolf Clausius (1822-1888) in 1850 [91]:

“There is a state function E, called ‘energy’, whose differential equals the work exchanged with the surroundings during an adiabatic process.”

The definition provided the basis for the basic energy balance used in nearly all building analysis today, given in Equation 1. It shows the change in energy being equal to the change in work and the change in heat, which is zero for an adiabatic process.
Introduction and Background

Equation 1  
\[ dU = \partial Q - \partial W \]

In the same work [91], Clausius also created the first theoretical basis for the second law of thermodynamics. His theory is what has become known as the Clausius Statement, which states that no process can have the sole result of heat being transferred from a body of lower temperature to a body of higher temperature. Lord Kelvin, after already developing the absolute temperature scale based on Carnot's work [92], formulated what is now known as the Kelvin-Planck statement of the second law of the thermodynamics, which states that it is impossible for any device that operates on a cycle to receive heat from a single reservoir and output work. The two statements have been shown to be equivalent and support the development of the Clausius equality in Equation 2, and the concept of entropy, named by Clausius in 1865 [93], and described in Equation 3. Both equations are for reversible systems, where \( dQ \) represents an infinitesimal exchange of heat across a boundary at temperature \( T \). This ratio defines the change in entropy, \( dS \), in Equation 3.

Equation 2  
\[ \oint \frac{\partial Q}{T} = 0, \text{ for a reversible process} \]

Equation 3  
\[ dS = \frac{\partial Q}{T}, \text{ for a reversible process} \]

Entropy is a path independent state function that facilitates the evaluation of the limitations in the operation of thermodynamic systems and cycles. The Clausius equality shows that for an ideal reversible process operating in a cycle, the change in entropy is zero. For actual evaluation we are interested in non-ideal irreversible processes. In this case, it is interesting to calculate the change in entropy as given in Equation 4.

Equation 4  
\[ \Delta S \geq \int \frac{\partial Q}{T}, \text{ for all processes} \]

The rule that the change in entropy of a system must increase is a corollary of the second law of thermodynamics. It led to Clausius' famous statement that the entropy of the universe is always increasing. The evaluation of the change in entropy and defines the level of dispersion in a system as illustrated in Figure 1.1, where a change in entropy occurs with no change in energy. Such types of irreversible changes in a system and the meaning of such formulations were explored in depth by Maxwell [94].

Figure 1.1 Representation of a change in entropy with no change in energy. No energy is added or removed from the container going from (a) to (b). But the entropy, or dispersion, in the container increases due to the free expansion of the particles.

The work of Lord Kelvin led to the development of the absolute temperature scale [92] and supplemented the development of the concept of entropy and the second law. It provided the first rational equation supporting the original work of Carnot, which had actually been one of the original inspirations for Kelvin to explore thermodynamics. This relationship, given in Equation 5, provides the limit the efficiency of an engine defined by the work
output, \( W \), and the heat input, \( Q \), when the engine is operating with a hot source at temperature, \( T_H \), and a cold source at temperature, \( T_C \), measured in the absolute temperature scale of degrees Kelvin. This Carnot efficiency of the engine firmly placed the ideas generated by Carnot into place as one of the cornerstones of the second law of thermodynamics.

*Equation 5*

\[
\eta_{\text{Carnot}} = \frac{W_{\text{max}}}{Q_{\text{in}, H}} = \frac{T_H - T_C}{T_H} = 1 - \frac{T_C}{T_H}
\]

The entropy of a system limits the potential of a system to produce work using heat, or more applicable for buildings, to supply heat using work. This is combined with the basic energy balance to provide a more complete view of the thermodynamics of any process. It is especially true for the evaluation of the potential and value of heat provided to buildings.

For buildings, direct combustion can be used to extract heat from chemically stored energy, or work can be used to extract heat from a cold temperature and deposit it in a warmer temperature, as done by a heat pump or air conditioner. In the worst case electricity is converted to heat by a resistance heater. Heat can be supplied or extracted using a district heating or cooling system to meet individual building demand in a large, generally compact, group. In all these processes the first law can be used to do an energy balance on the transfer of heat to the building. The energy balance is used to add up the incoming and outgoing heat fluxes of a building to determine its overall heat demand (dependant on external environmental conditions) such that heat supply or removal can be provided to maintain a comfortable indoor environment. A simple energy balance provides the basis for the evaluation of the vast majority of building systems.

The concepts of heat and mass transfer and fluid dynamics come into play when the rate of energy and heat movement within a building must be known. This knowledge is needed, for example, to determine the rate of heat loss through a building wall, the movement of air between adjacent rooms or from the ventilation system, or the addition of heat from solar radiation through windows. These three heat exchanges represent the three types of heat transfer, respectively, conduction, convection, and radiation. They are all essential parts of completing an energy analysis of a building. The individual aspects can be calculated at various levels of precision. For complicated fluid flows and radiation inputs, assumptions are often made in prescriptive building evaluations \[95-97\], but the combined energy balance always provides the final resulting demand.

Still, the overall energy analysis of a building only captures the raw quantity of energy being moved into and out of the building and its various systems. The second law of thermodynamics allows one to observe the more subtle differences in the quality of the energy being used.

The second law and the concept of entropy provide a view of the irreversibility of a system, and thus how close it is to ideal operation. In the case of the main thermodynamic process of heat transfer in buildings, the principle is important because heat transfer across a temperature gradient is inherently irreversible, as described by Clausius’ statement previously quoted that heat will always flow from hot to cold. Nevertheless, the historic abundance of energy sources, especially for simple combustion, has led to the standard use of combustion to supply heat to buildings based solely on the energy demand and the first law of thermodynamics. Considering the second law of thermodynamics helps to further improve the operation of buildings by reducing dependence on highly irreversible processes.
that are designed without consideration for the second law of thermodynamics or the generation of entropy.

What is often of more interest in the case of entropy is the change that takes place within a closed system such as a building or building system. In this case, an entropy balance can be done in addition to the energy balance in order to analyze the closed process, and there have been entire optimization systems developed around entropy minimization [41]. Relative to buildings, entropy itself is not used specifically for the analysis of the entire building, but it is a fundamental part of the exergy concept, and is the part of a quantity of exergy differentiating it from energy. By incorporating entropy in to the energy concept, a more accurate picture of the potential of said energy is presented in the form of exergy. Exergy can then account for losses due to the second law and irreversibility. Entropy allows exergy to expose the differences in the quality of various states of potential energy sources supplied to and used in buildings.

1.5.2 Exergy Fundamentals

The idea of how to represent the true potential energetic output of a system based on the rules set forth by the second law of thermodynamics was already generated in the mathematical formulations of Gibbs in the 19th century. His ascertains allowed the “available energy” of a systems to be calculated based on it surroundings [98]. The Guoy-Stodola theorem formalized an equation for the available energy. It was developed independently by Gouy [99] and Stodola [100]. Throughout the 20th century the chemical industry often used the idea of “available energy” for process optimization. Exergy, defined as a single term to represent this potential, was coined by Rant in the 1950s [101, 102]. It facilitated a more simplified analysis of systems with a unified concept. The concept was quickly adopted across Europe, and an expanded definition was given by Baehr in 1962 [42], that further defined exergy as energy, or the part of energy, which could be converted into any other form. Still, as for the term exergy, there remained a significant contingent, mostly in the United States, that still focused on “availability analysis” as described in the book by Moran from 1982 [103]. But more recently the term exergy has been universally accepted, and is a part of standard curriculum, including the most recent work from Moran [39] and the Encyclopedia of Energy [104]. Exergy was developed as a tool to assist in the optimization of thermodynamic systems. It is defined as the combination of the potential change in energy and entropy of a system when interacting with its surrounding environmental conditions. The surrounding conditions are referred to as the reference environment or dead state. The reference environment provides a realistic comparison of a system to its surroundings, and thus allows exergy to better define the real potential to extract energy from a system as it interacts with its environment. In the case of a thermal cycle that develops work from a heat input, the natural flow of heat from hot to cold (Clausius statement of the second law) is exploited to generate work, but the generation of that work depends on the existence of that flow of heat, and for that flow to exist, some of the heat must actually flow to the cold sink. Therefore it is impossible for all the heat to be converted to work (Kelvin-Planck statement of the second law), and this limited amount of work is quantified by exergy. The requisite flow of heat to the cold sink is defined as anergy, or energy that will be dispersed and go to equilibrium with the surroundings, i.e. the reference environment. An absolute quantity of exergy is defined relative to a reference environment as shown in Equation 6, where the Exergy, Ex, is a combination of the difference between the total
energy, \( E \) (potential, kinetic, and internal), subtracted by the energy at the reference environment, \( U_0 \); the net work input or output given by the pressure, \( p_0 \), and volume relative to the volume, \( V \), at the reference environment, \( V_0 \); and also the difference between the entropy of the system, \( S \), and the entropy of the reference environment, \( S_0 \), multiplied by the temperature of the reference environment, \( T_0 \). The first two terms give the relative quantity of energy available in the reference state, while the third term describes the quality of the system. The reference environment is usually defined as the state whereby the system would be at equilibrium with its complete external environment. In the case of a building the reference temperature is often debated depending on the system being analyzed, but for most analysis, the outside conditions are taken.

\[ Ex = (E - U_0) + p_0(V - V_0) - T_0(S - S_0) \]

This absolute quantity is not very useful. When looking at various systems and processes within a building, it is of more interest to calculate changes in exergy in various systems. In order to make this calculation, one must create an exergy balance by combining the energy balance and the entropy balance. The energy balance from the first law of thermodynamics given in Equation 1 can be integrated to provide a change in energy, \( U \), in a process from state 1 to state 2, as shown in Equation 7. The entropy term, \( \dot{S} \), in Equation 3 can also be integrated. In this case for non-ideal processes the change in entropy is augmented by the entropy generated, \( S_{gen} \), by irreversibilities in the system. The change in entropy is give in Equation 8.

\[ U_2 - U_1 = \int_{1}^{2} \dot{Q} - W \]

\[ S_2 - S_1 = \int_{1}^{2} \frac{\dot{Q}}{T} + S_{gen} \]

By combining these energy and entropy balance equations the exergy balance shown in Equation 9 is generated. It gives the difference in exergy, \( Ex \), from three terms. The first term is the exergy change due to heat transfer, where the infinitesimal heat transfers, \( d\dot{Q} \), are integrated and subtracted by the integration of those multiplied by the ratio of the reference environment temperature, \( T_0 \), to the temperature at the boundary which the heat transfers take place, \( T_b \). The second term is the exergy transfer that accompanies work described by the work done by the system, \( W \), subtracted by the reference environment pressure, \( p_0 \), times the difference in volume between the beginning and end state, \( V_2 - V_1 \). The last, and important term, is the exergy destroyed, which is the reference environment temperature, \( T_0 \), times the entropy generated by the process, \( S_{gen} \). Unlike energy, which is conserved, exergy can be destroyed by irreversibilities in the system or process.

\[ Ex_2 - Ex_1 = \int_{1}^{2} \left( 1 - \frac{T_0}{T_b} \right) d\dot{Q} - \left( W - p_0(V_2 - V_1) \right) - T_0 S_{gen} \]

One of the main advantages of exergy analysis is the ability to calculate exergetic efficiencies. Efficiencies are ratios of output to input, and typical energy efficiencies are often misleading because using the total input is not always realistic. Due to the second law the total heat input or output from the thermodynamic cycle can never be equal to the total work input or output, and is limited by what is called the Carnot efficiency. Thus the fraction of potential performance is not actually described by the efficiency, only the fraction of input energy used. Exergy analysis allows the theoretical maximum output to be calculated, limited by the 2\(^{nd}\) law of thermodynamics, and then that can be observed as compared to the actual output. In this way a more realistic goal for optimization can be guaranteed [44].
In a fundamental sense, the exergetic efficiency can be calculated by the exergy output of a system divided by its input as shown in Equation 10. For a thermodynamic cycle this can be shown to be the ratio of the work out, $W$, to the heat in, $Q$, multiplied by the ratio of one minus the reference environment temperature, $T_0$, to the temperature of the work transfer output, $T_W$, and of the heat transfer input, $T_Q$.

\[
\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} = \frac{W}{Q} \frac{1 - \frac{T_0}{T_W}}{1 - \frac{T_0}{T_Q}}
\]

However, in some cases the total exergy input is not all available for use by the output process. Then it becomes more useful to compare the desired exergy output to the actual exergy used. This has been defined in Equation 11 by the rational exergy efficiency, which is described by Kotas [43].

\[
\psi = \frac{Ex_{desired}}{Ex_{used}}
\]

Finally, in real processes there is usually a complex set of energy flows, and the rational exergy efficiency can be somewhat subject to what is desired and what is actually used to produce the desired output. In some cases the exergy output includes some exergy that simply transits through the system. There are also separate exergetic losses, some internal to the system and some external. Therefore the consumed exergy during the process is really the total exergy input minus that which has transited the system, and the produced exergy that is used is really the consumed exergy minus the internal and external losses and not including the transiting exergy. This has been defined as the utilizable exergy coefficient by Brodyansky [44], $\eta$, and is given by Equation 12. The exergy flow previously displayed is shown graphically in Figure 1.2 [6].

\[
\eta_{produced,utilizable} = \frac{Ex_{out} - Ex_{transit}}{Ex_{in} - Ex_{transit}} = \frac{Ex_{produced,utilizable}}{Ex_{consumed}}
\]

Figure 1.2: Representation of the flow of exergy for analysis using the produced utilizable exergy coefficient [6].
The flow of exergy in building systems can be quantified and optimized. This can be used to improve the performance of the components within individual systems or to optimize the building system as a whole. The concept of exergy can actually play many roles in building operation, and can be utilized for system analysis, as well as conceptually in the design process. These roles are explored in this research and specifically in Chapter 1 where the application of exergy and anergy utilization for buildings is explored further.

### 1.5.3 Exergy and Buildings

In order to apply the concept of exergy to buildings a form is derived that can be used for heat and energy flows. In this case the equality is adapted for the flow exergy, \( \dot{e}_x \), based on the specific enthalpy, \( h \), and specific entropy, \( s \), of the system, and the kinetic and potential energy of the flow. This is given in Equation 13 adapted from Equation 6.

#### Equation 13

\[
\dot{e}_x = (h - h_0) - T_0 (s - s_0) + \frac{1}{2} v^2 + gz
\]

The flow exergy is used to setup the exergy balance for open systems, which is needed for building system analysis. It is given in Equation 14 for a flow with single input and output and a single heat input and work output. The last term contains the entropy generated by the systems and is the exergy destruction rate in the process, Equation 15. This is the factor that is minimized in exergetic optimization of thermodynamic systems.

#### Equation 14

\[
\frac{d \dot{E}_x}{dt} = \dot{m}_i \dot{e}_x_i - \dot{m}_o \dot{e}_x_o + Q_{in} \left( 1 - \frac{T_0}{T_i} \right) - W_{out} - T_0 \dot{S}_{gen}
\]

#### Equation 15

\[
\dot{E}_x_{des} = T_0 \dot{S}_{gen}
\]

For the exergy analysis of building systems, all properties of every system cannot be determined and approximations are used. The enthalpy and entropy are calculated by assuming a constant specific heat, \( c_p \), as given in Equation 16 and Equation 17.

#### Equation 16

\[
h_2 - h_1 = c_p (T_2 - T_1)
\]

#### Equation 17

\[
s_2 - s_1 = \int_1^2 \frac{\partial Q}{T} = \int_1^2 c_p \frac{dT}{T} = c_p \int_1^2 \frac{1}{T} dT = c_p \ln \frac{T_2}{T_1}
\]

The exergy flowing out of a system in a building can be simplified from Equation 13 and Equation 14 using Equation 16 and Equation 17. For a simple heat flow, for example through a heat exchanger connected to a closed loop, the kinetic and potential energy can be neglected, and the external flow of heat and work can be assumed to be zero, leaving the simplified version in Equation 18. In this case internal frictional losses or other irreversibilities are contained with the destroyed exergy term, but this can also generally be neglected for very simple building calculations.

#### Equation 18

\[
\dot{E}_x_{flow} = c_p \dot{m} \left( T_{out} - T_{in} - T_0 \ln \frac{T_{out}}{T_{in}} \right) - \dot{E}_x_{gen}
\]

Also for buildings, simple flows of heat can be easily represented in terms of exergy based on the heat contribution defined in Equation 14. The quantity of heat is simply multiplied by the a factor equivalent to the Carnot efficiency from Equation 5, which is logical because it redefines the exergy of the heat in terms of its maximum potential to produce work. Thus the exergy of the heat flows in the building can simply be approximated by Equation 19.
Introduction and Background

Equation 19

\[ \hat{E}_{\text{heat}} = \dot{Q}_H \left(1 - \frac{T_0}{T_H}\right) \]

The goal of using the concept of exergy for buildings is to optimize the operation. This requires all the heat transfers and energy flows to be considered in terms of exergy. The results demonstrate where excess amounts of exergy are used. The goal of heat transfers and flows in the building are to provide the building services that provide comfort, which primarily consist of space conditioning along with water heating for residences. The conditioned air in a building creates the final exergy demand that must be met by the building systems. Interestingly, this exergy demand is actually quite low due to the relatively low temperatures in building operation. Also this demand is dependent on the reference environment. The exergy demand of room air at 20 °C is shown in Figure 1.3 for cold winter conditions and warm summer conditions. During the winter the room air contains warm exergy and in the summer it contains cool exergy, as described by Shukuya [6], which is an important consideration for buildings. Instead of an absolute definition of an amount of energy in a system, exergy provides a more useful illustration of the potential of that system relative to its surroundings. It is especially useful in creating an understanding of cold exergy for cooling applications in buildings [105].

![Figure 1.3: Exergy of room air at 20 °C plotted on the y-axis versus the outdoor reference environment temperature, T₀, on the x-axis from -10 °C to 40 °C. This demonstrates the difference between the warm air of the exergy during winter conditions to the left and the cool exergy of the room air during summer conditions to the right.](image)

Now consider the exergy of the typical combustion sources used to heat buildings with temperatures on the order of hundreds of degrees higher than air temperature. If the temperature outside is 0 °C, then the exergy demand of the room air is relatively low, but consider the amount of exergy in a source hundreds of degrees higher. A large amount of exergy is lost when these high temperature source are dispersed into low temperature room air. Even if a high percentage of the raw energy from the source goes into the room air, exergy analysis demonstrates the inefficiency in using these high exergy sources for low exergy room air. It is the idea of matching low exergy systems to the low exergy demand of building heating and cooling.

The amount of heating and cooling exergy demanded by the building changes for different outside conditions, because the outside conditions represent the final sink and the surroundings of the system. Therefore the outside conditions make sense as the reference environment when calculating the exergy of the room air. But for the various building subsystems a reference environment also has to be fixed, and some of the various supply
and distribution systems do not interact directly with the outside. Nevertheless, the outside air is the final sink these systems, as will be argued in Chapter 1, and it is used for all the building systems to generate a comparable result, and a comparable quantity of exergy for each system in the building.

Systems such as heat pumps can be analyzed in more depth for the exergy consumption of individual components, as done by researchers at HSLU [3]. In this case the analysis is actually taking place inside the building subsystem itself and a different reference environment may be appropriate to evaluate the machine performance independent of the building. But when integrated building systems are analyzed as a whole, the reference temperature is set to the outside conditions. The broader analysis considers the entire chain of exergy usage in a building as described by Schmidt [9, 19]. In this way various types of primary energy inputs can be correctly valued, as described by Baehr [42], where inputs in the form of electricity represent pure exergy, because it can be 100% converted into other forms of energy. Furthermore, this thesis will explore the appropriate allocation of free or renewable sources of exergy utilized from the environment versus delivered exergy from thermal combustion processes. Heat pumps provide an excellent opportunity using a thermodynamic cycle to extract free exergy in the form of heat from the environment, which can be matched in both quantity and quality to the exergy demand of the building.

1.5.4 Heat Pumps

Heat pumps are a major component in the analysis. Heat pumps use energy to pump heat from a cooler source to a warmer sink. Using a thermodynamic cycle, one unit of energy can mobilize many more units of heat, limited by Carnot efficiency as described above. Compared to fuel combustion systems, one unit of fuel energy can only provide at most one unit of heat energy. This limit makes heat pumps an attractive option for energy demand reduction, because there is much more potential for increases in performance, and they are capable of operating at temperatures closer to the building temperature, thus reducing the inherent exergetic losses caused by large temperature gradients.

Heat pumps operate in a thermodynamic refrigeration cycle. The efficiency of a heat pump is defined by the coefficient of performance as given in Equation 20, which is the ratio of heat supplied (or heat removed for an air conditioner) to the work (or electricity) input. The maximum possible value when no irreversibilities are present in the machine is given in Equation 21 as the ratio of the temperature at which the heat is supplied to the difference between the supply temperature, $T_H$, and the source temperature, $T_C$, also referred to as the temperature-lift. This ideal performance represents the theoretical limit that a machine can achieve. For example, if a heat pump has to supply heat at 30 °C to a room and supplies it from a source at 0 °C, the maximum theoretical, $COP_{max}$, would be 10. So in theory 10 units of heat could be transferred with one unit of electricity. Nevertheless, machines typically do not come close to operating at this theoretical maximum. Equation 22 shows how the actually COP of a heat pump can be calculated as a ratio of its performance to the ideal performance using a Carnot efficiency or g-value (Gutegrad), g. Exergy analysis can help reduce the irreversibilities, but most machines operate with a Carnot efficiency ranging from about 0.4 to 0.6 [50], so that theoretical heat pump would probably have a COP of about 5 in this case.

**Equation 20**

$$COP_{HP} = \frac{Q_{out}}{W_{in}}$$
Equation 21
\[ \text{COP}_{\text{max}} = \frac{T_H}{T_H - T_C} \]

Equation 22
\[ \text{COP}_{\text{HP}} = g \frac{T_H}{T_H - T_C} \]

Clearly, the temperature-lift is a crucial factor in heat pump efficiency. The smaller the lift, the higher the possible COP, as illustrated by the work done the papers in Chapter 1 shown below in Figure 1.4.

\[ \text{COP}_{\text{max}} = \frac{T_H}{T_H - T_C} \]

\[ \text{COP}_{\text{HP}} = g \frac{T_H}{T_H - T_C} \]

\[ \text{COP} \]

\[ g \]

\[ T_H \]

\[ T_C \]

\[ \text{Nonfeasible} \]

\[ \text{Typical HP} \]

\[ \text{LowEx HP} \]

Figure 1.4: Increase in COP with decreasing temperature-lift of the heat pump.

Cycles have been developed that use a system of vapor compression, reversed Brayton or Stirling cycles, gas-acoustic effects liquid-vapor absorption, liquid-solid adsorption, and also using the thermoelectric effect \[106\]. Of most interest here will be the vapor-compression cycle, particularly its implementation in systems with very low temperature-lift.

The main advantage of using heat pumps is that they are ideal for low exergy design. Compared to a typical boiler system, the heat pump extracts the heat at a lower temperature and can be designed to provide heat at any temperature. In this way the exergy destroyed by heat transfer across large temperature gradients can be minimized. Heat pumps can also be designed with a reversible valve to allow for operation in a cooling mode during summer.

Minimizing the temperature-lift of heat transfers is the principle behind low-temperature heating and high temperature cooling. By using large surface areas and low temperatures in the space heating or high temperatures in the space cooling the exergy destroyed in the transfer of heat to the room is minimized. This can only be achieved though, when the building is also well insulated, because the low temperature gradient and maximum surface area available limit the rate at which heat can be transferred into the space \[6\]. Systems of low temperature and large surface area heat transfer have been analyzed, and when implemented they can greatly reduce the exergy loss and reduce the energy demand of the building significantly \[107, 108\].
1.6 Overall Perspective

1.6.1 Overall Context

This thesis presents a broad picture of the usage of the concept of exergy for integrated building systems including an extensive literature review and theoretical explanation (Chapter 1). The initial work and primary analysis demonstrates the use of exergy analysis in the evaluation of wastewater heat recovery to minimize temperature gradients for the exergy intensive process of providing domestic hot water (Chapter 2). The initial work provides a fundamental basis for further work designing and analyzing the feasibility and performance of a novel façade system that was a result of considering exergy and anergy flows around buildings (Chapter 3). It generates the impetus to further explore the meaning of exergy and anergy as applied to buildings, and how a more useful method of exploiting these concepts can be developed for buildings that also addresses the issue of defining the reference environment (Chapter 4). The broader perspective for utilizing exergy and anergy for buildings helps to reveal the larger benefits achieved by integrating low exergy systems that combine good anergy sources and low exergy supplies with low temperature-lift heat pumps (Chapter 5). These larger benefits are included in a review of the technological and methodological opportunities to eliminate CO₂ emissions from the building sector (Chapter 6). Finally, the significance and implications of this work are discussed along with potential future work (Chapter 7).

1.6.2 Initial Models

The work in wastewater heat recovery produced several models that are presented in Chapter 2. They give a picture of the initial view of the building system. The initial ideas were focused on minimizing the temperature-lift of the heat pump by considering a two-stage heat pump that could operate for both space heating and warm water production. These types of heat pumps already exist [73], and the system would be novel as well as low exergy because the second stage would operate with the high temperature recovery from the wastewater. Such an operation resulted conceptually in the first integrated low exergy building model shown in Figure 1.5.
Figure 1.5: The is the first model developed to illustrate the potential recovery of warm wastewater to increase the performance of a dual stage heat pump. The heat pump can operate with a ground source of around 5 °C to supply space heating at 30 °C, and it can also recover heat when hot water is used at 15 °C (accounting for some mixing) in order to supply warm water at 50 °C. The illustration also shows the integration of exhaust air heat recovery and the supply of space heating while hot water is produced through a two-stage heat exchanger.

The initial model for wastewater heat recovery was a simple representation of the operation of the wastewater heat recovery concept. It guided some of the initial analysis and thinking about low exergy systems. The conceptualization of the integrated system was extended to include more potential sources and the use of renewable energy. It is shown in Figure 1.6; with the goal being to demonstrate how zero CO₂ emissions can be realized through integrated low exergy systems and a high performance heat pump with a COP of 8. It was used in the third paper of Chapter 3 to demonstrate the operating potential of the system, but did not yet incorporate the coupled model of the heat pump. Rather, the performance is based on the temperature-lift calculations. These were made based on the real temperature outputs modeled from the heat recovery analysis.
Chapter 1

Figure 1.6: This is an illustration of the potential operation of a heat pump with a high COP through the integration of wastewater heat recovery along with other higher temperature sources of heat from the air and ground, as compared to typical outside conditions.

A more accurate flow diagram was developed to show actual heat flows in the system. It provided a generic conceptualization of the system, and it also provided a framework to present some of the modeling results. This model is shown in Figure 1.7.

Figure 1.7: Model used to show the heat flow for wastewater heat recovery. The generic model is shown to the left and the implementation with actual values calculated from the analysis in Chapter 2 is shown to the right.

Finally, in collaboration with Ritter for the second paper in Chapter 5, an illustration was developed to demonstrate the performance of an example low exergy system, which integrated multiple components. The model did not address wastewater heat recovery directly, but rather the supply of hot water heating through a network of exergy and anergy supplies. The model was developed for the heating and cooling case as shown in
Figure 1.8: Integrated low exergy system model developed with Ritter in Chapter 5 to illustrate the combination of the hybrid photovoltaic system, dual-zone borehole, and heat capture for an optimal supply of heating, cooling, and hot water.

The models developed progressed the overall perspective of the low exergy system. They helped to instigate the final discussion on the implications of integrated low exergy systems, and supported the consideration for the global implications for better building design and reduced greenhouse gas emissions. Finally, they contributed to the generation of the final representations for the low exergy given in the master model.

1.6.3 Master Model

The primary work on wastewater heat recovery contributed to the larger concept of integrated low exergy systems, which led to the development of a broader picture of the overall system. An expanded master model has been created that illustrates the concepts of wastewater heat recovery as well as the new concepts and ideas covering the active façade system, the reference environment, and the integration of further low exergy system such as hybrid photovoltaics. The model, presented in Figure 1.9, provides a picture of how the ideas presented can be combined together and how the ideas influence one another. In general, the systems and concepts work together towards the objective of this thesis to evaluate and design buildings with regard for the second law of thermodynamics in a way that improves performance.
Figure 1.9: Master Model – the model illustrates the majority of the concepts presented in this thesis. The concepts are labeled by chapter they are presented in, including the wastewater heat recovery from Chapter 2 with its low temperature lift wastewater heat pump for hot water production, the active low exergy geothermal wall insulation system from Chapter 3 that uses a circulation pump to provide ground heat to the external area of the building wall. Also the concept of utilized exergy, consumed exergy, and anergy sources from Chapter 4 are given, along with the labeling of the reference environment for the entire building system. Finally, the hybrid photovoltaic and ground storage concepts are illustrated in combination with the low temperature-lift heat pump from the integrated low exergy systems presented in Chapter 5.
1.7 References


Introduction and Background


Introduction and Background

97. SIA, SIA 380/1 V5. 2009.
Chapter 2

2 Wastewater Heat Recovery

2.1 Overview and References

A model is developed that analyzes the potential of wastewater heat recovery for integration into a low exergy system.

Papers:

AIVC:

PLEA:

CISBAT:

Energy and Buildings
2.2 Context of Papers

There are four papers that are presented in the context of wastewater heat recovery. This section contains the most papers because this topic initiated this research into low exergy integrated systems. These papers describe the various models and analysis that were used to evaluate the potential of a wastewater heat recovery system. The final goal was to determine the potential for this higher temperature source to improve the performance of warm water generation. This is because, as described in the papers, warm water presents one of the biggest challenges when it comes to low exergy system design.

This challenge is what makes this an innovative application of exergy analysis. Hot water not only has an unpredictable stochastic usage pattern, but it also demands a higher temperature. This means that per unit heat, there is more exergy demanded by hot water production. It also means that per unit heat, the waste flow from this system also contains the most potent source of exergy. These papers analyze the potential of capturing this source to logically help minimize the exergy demand from the hot water system itself, with its large exergetic demand.

The first paper was presented at The 29th AIVC Conference in 2008 – Advanced building ventilation and environmental technology for addressed climate change issues. It is titled, “Unique Integration of Hot Water Heat Recovery into Low Exergy Heating.” The analysis focuses on the exergetic performance of the heat recovery from the wastewater assuming a recovery tank is placed in the wastewater system. The tank is assumed to be fully mixed and a statistical set of annual hot water events are used to analyze the potential performance of the system. This analysis gave the first result that illustrated the difference in performance evaluation when exergy is used versus energy. The results also provided the basis for a discussion comparing the potential of wastewater heat recovery to that of exhaust air heat recovery, which is a much more common practice. The second paper was presented at the PLEA 2008 – 25th Conference on Passive and Low Energy Architecture. It is titled, “Exergy Recovery from Warm Wastewater for an Integrated Low Exergy Building System.” It provides a simple extension of the initial model and the first paper. It demonstrates the increase of performance that is possible when a stratified tank model is used, which allows warmer temperatures to be extracted from the top of the recovery tank. In both of these first two papers the potential influence on the performance of an integrated heat pump is discussed, but not explicitly incorporated into the model.

The third paper was presented at CISBAT 2009 International Scientific Conference – Renewables in a Changing Climate from Nano to Urban Scale. It is titled “Exergy and Building Systems: Full Potential of Heat Recovery.” This paper was the result of an extended analysis into the influence of the building size. The initial models were based on a simple dataset of water usage for a single family dwelling in the United States, and this was extended to a larger potential number of residences and the statistics that better represent European multi-family housing was used.

Finally, the research into wastewater heat recovery culminated in the paper accepted into the journal Energy and Building with the title “The potential of wastewater heat and exergy: decentralized high-temperature recovery with a heat pump,” which explicitly incorporates the operation of a low temperature-lift heat pump into the model. This allows the direct calculation of exergy input into the system to provide domestic hot water, while recovering the heat from its usage. The impact of the optimized exergy recovery that demonstrated in the first papers is integrated into a complete system that maximizes the performance of a heat pump. The results show that a very high COP in the range of 6-8 can be achieved with
such a system, drastically reducing the exergy input necessary to produce domestic hot water as compared to that utilized by typical combustion systems.

These research papers have created a significant proof of concept for the utilization of heat from wastewater heat to optimally generate domestic hot water. Although the results are theoretical, the implications of such performance could dramatically reduce the primary energy demand for buildings, especially high performance buildings that often have space heating and cooling demand optimized, while hot water heating remains a significant overlooked demand.

In the context of this research into low exergy systems, this research provides the theoretical basis and the initial groundwork for analysis of integrated low exergy systems. The consideration for how systems can be combined to maximize the performance of a heat pump and minimize building demand is illustrated, and this provides the impetus for a similar evaluation of other systems. It also verified the use of exergy analysis for the consideration building systems, not just in terms of energy, but also contemplating the value of that energy with reference to the supply and utilization temperatures.
**Paper 2.1: Unique integration of hot water heat recovery into low exergy heating**

Forrest Meggers and Luca Baldini


**Abstract**

There are many technologies aimed at reducing energy demand of ventilation systems, but the focus in these designs has remained on the air heating system and exhaust losses. In fact, a typical daily exhaust air requirement for one person has the same quantity of exergy as the water from a typical shower, therefore heating systems must also consider hot water.

This project presents the exergy analysis of integrating wastewater heat recovery into a building heating system. A heat pump provides room conditioning and hot water heating. The “low exergy” heating minimizes the temperature lift required by the heat pump as well as the temperature differences at heat transfer surfaces in the heating system. This maximizes the performance of the heat pump and minimizes the exergy destroyed in the system. An exergy analysis provides a detailed look at the energy demand and the appropriateness of the quality of the energy utilization. The exergy analysis of the system is part of the research in the Swiss participation in the IEA ECBCS Annex 49: Low Exergy Systems for High Performance Buildings and Communities.

The analysis shows that the exergy available in warm wastewater can be used to augment the evaporator temperature of the heat pump. The room heating system functions with large heat transfer surface areas (i.e. TABS) at 30 °C, and when hot water needs to be produced at higher temperatures, the temperature lift of the heat pump remains low by augmentation from hot wastewater. The optimization and performance characteristics of this high performance system are presented.
Introduction

Motivation
Buildings are like living organisms. They breathe air in and out. They ingest water and materials and excrete waste. They also utilize energy to function. Still, organisms have had millions of years to optimize their systems, and the comparatively short existence of buildings leaves room for their improvement.

Two major improvements focused on today are reduced energy requirements and better indoor environmental quality. This brings attention to building ventilation and energy strategies, but often overlooks their integration into a complete system. For example, the energy used to condition air is often considered, but the energy used to condition other incoming flows like water are often not considered. While exhaust air heat is often recovered in modern ventilation systems, the potential of warm wastewater is almost always lost. In fact, it will be shown that the amount of heat in exhaust air for one person for one day is similar to the amount of heat for a typical shower for that person. Therefore a system that captures both of these potential losses should be considered. The heretofore neglected integration of wastewater heat recovery into a system will be the focus here. The goal is to implement this system into a low exergy building that minimizes the use of high value or high temperature energy. In order to optimally integrate these systems with their various heat fluxes, the concept of exergy is employed to account for changes in both quantity and quality, reducing primary energy consumption.

Summary
This study will present the exergy analysis of a wastewater heat recovery system. It will model realistic hot water usage data on a fine time scale to allow for optimal heat extraction at the highest possible temperatures. It will show the high exergy content of wastewater and compare it to the exergy content of exhaust air. The utilization of this exergy in an integrated system will be described, and make the case for a low exergy building in which temperature gradients are minimized and high temperature heat sources are avoided. Therefore the system will incorporate a heat pump. Both the exhaust air and wastewater exergy would be recovered in the system by the heat pump to minimize the temperature lift it must provide.

Using a wastewater heat recovery system minimizes exergy consumption, and is ideal for an integrated low exergy building system.

Background

Exergy
Exergy is a concept that combines the first and second laws of thermodynamics by combining the basic energy and entropy balances. This presents a view where it is possible to consider energy quantity as well as quality in one value. This improves energy systems and leads to better energy policy (Rosen, 2008)

Exergy is defined by the energy adjusted for the quality as accounted for by entropy. This is given in Equation 1 where $Ex$ is the exergy, $Q$ the heat transfer, $T_0$ the reference temperature, and $\Delta s$ the change in entropy (Ahern, 1980).

\[ Ex = Q + T_0 \cdot \Delta s \]  

(1)
In the case of the exergy change of an incompressible fluid, the energy term can be approximated assuming a constant heat capacity, and the entropy term can be estimated by the natural logarithm of the ratio of the temperature change as shown in Equation 2 where \( m \cdot \) is the fluid mass flow rate, \( c_p \) the fluid heat capacity, \( T_h \) the warm input temperature and \( T_c \) the cool output temperature (Schmidt, 2004).

\[
Ex = m c_p \left( T_h - T_c - T_0 \ln \frac{T_h}{T_c} \right)
\]  
(2)

Exergy includes a term, \( T_0 \), that accounts for the conditions of the external environment relative to the system. This allows one to evaluate the quality of the energy in a system. A temperature farther away from the environment has more potential, thus more quality or exergy.

For energy alone, a balance can always be made. But in the case where one has a volume with the same amount of energy but with different temperatures, the potential to do something useful with the higher temperature volume is greater, even though it has the same amount of energy. The higher potential is quantified by exergy. Exergy accounts for the potential for an amount of energy to do work based on its state as compared to the state of its surrounding environment (Ahern, 1980) (Moran, 2000).

The definition of the external environment, \( T_o \), is fixed for most systems operating in controlled environments, but for large scale systems like buildings it can be assumed to be fixed for certain systems, but in most cases it is taken as the outside conditions. For steady state analysis of heating systems or cooling systems this can be the design or the average conditions (Shukuya, 1994) (Schmidt, 2004).

Another term that is often used along with exergy is anergy. This refers to exergy that has been destroyed or is at the environmental state. It is no longer able to do work relative to the defined environment, and therefore another name for the environmental state is the dead state. Although work cannot be created from this state, work can be done in a thermodynamic cycle to extract anergy from the dead state as is done by heat pumps.

**Low Exergy Buildings**

Buildings that are considered to have low exergy systems utilize the concept of low temperature heating and high temperature cooling. This minimizes the temperature gradient between the room air and the heat source, thus minimizing exergy destruction. In order for adequate heating or cooling to be supplied with low temperature gradients a large surface area is needed like TABS or chilled beams along with a well-insulated envelope. An extensive overview is found in the IEA Annex 37 Guidebook (2003) and at www.lowex.net.

In this study an important aspect of low exergy buildings is the elimination of the use of high temperature heat. This clearly makes combustion technologies undesirable. High efficiency heat pumps are the ideal solution, and therefore it is of interest to optimize them for use in low exergy systems.

**Heat Pumps**

The laws of thermodynamics allow a heat pump to transport up to a certain amount of heat per unit of work input into the system. This value (heat moved/energy input) is the coefficient of performance (COP) and it has a theoretical maximum defined by a reversible Carnot cycle given in Equation 3 with \( T_H \) being the hot condenser temperature and \( T_c \) being the cool evaporator temperature (Moran, 2000).
A real heat pump has an efficiency less than the Carnot efficiency due to losses in the system. Still, it is clear that the potential of heat pump performance is dependent on the temperature lift it must provide. The exergetic performance of heat pumps has been studied by Gasser et al. (2008), Ozgener (2007), and Bilgen (2002) among others, and the research shows the potential for better optimization of heat pump systems through the use of exergy analysis.

The use of heat pumps for the production of hot water is well known (IEA Heat Pump Centre, 1993). The application of heat pumps for hot water production is expanding as fossil fuels become more costly (Waide, 2008). New methods of measuring seasonal efficiency of integrated hot water and space conditioning heat pumps have been developed, and consider exergy (IEA Heat Pump Centre, 2006).

How Water Usage

Most hot water usage is found in domestic systems, with the most concentrated usage found in large hotels or apartment complexes.

In order to realistically consider the potential of using energy from hot wastewater, one must consider how and when hot wastewater is produced. Unlike ventilation, the usage is sporadic and unpredictable (Shove, 2003). For an accurate look at the recovery of exergy from this system, realistic usage must be considered (Jordan, 2001).

Methods

Data Acquisition

The data used for the simulation of the hot water usage came from a probabilistic simulation engine developed at the University of Kassel (Jordan, 2003). The data was produced from the engine for the US DOE based on usage profiles for showers, baths, sinks, laundry, and dishwashers (Hendron, 2007). This provided randomized data at 6-minute intervals for each use that fit the statistics developed for each profile for a two, three, or four bedroom residence. The data is provided for baths, showers, sinks, laundry, and dishwashing loads. There is data for pure hot consumption or for the hot-cold mixes of baths, showers and sinks. The temperatures of the usage are taken from Hendron (2007). The data for four bedrooms was used and the entire year was compiled into one input for simulation in Matlab.

Analysis

The simulation uses the flow of hot water over time along with its temperature from the data mentioned above. The result is sent into a modeled recovery tank with a set diameter, volume, and wall heat transfer coefficient. The tank contains a heat exchanger having a set flow rate, supply temperature and pipe diameter, and is modeled in a spiral. The spiral width is sized relative to the tank diameter, and the spacing between turns is set at three pipe widths.

At each time step the simulation checks if a hot water event occurred and the amount of water going into the tank. The temperature of the incoming water is adjusted from the given values (Hendron, 2007) so that losses during flow to the tank and losses during use

\[
COP = \frac{T_H}{T_H - T_C}
\]
are considered. These are estimated to be 5, 3, 2, 5, and 2 percent for bath, shower, sink, clothes and dishes respectively.

If an event has occurred, the new volume of the tank is calculated. There is a valve that is activated if the tank is filled to capacity. It removes liquid from the bottom of the tank, so if the new volume is greater than the capacity, the previous water is removed to make space for new input.

New events are combined using an energy balance with what is in the tank. This calculates the new temperature of the tank assuming it is completely mixed. The heat exchanger in the tank is assumed to have a heat transfer coefficient, which depends on the depth of liquid in the tank. The actual heat transfer rate depends on the calculated temperature in the tank and the heat transfer coefficient. The heat extraction is modeled as a laminar flow through a pipe with constant surface temperature equal to the tank temperature. The heat extracted from the tank and the heat losses through the walls are removed from the tank using an energy balance to determine the new temperature. This provides the temperature of the tank for the next time step. If the temperature has dropped below a set point that is two degrees above the heat exchanger supply temperature, the tank is flushed completely and waits for the next event.

The amount of exergy available from the wastewater is calculated from equation 2 and the amount of heat extracted by the heat exchanger at each step. This is compared to what would be available from exhaust air at room temperature. The reference temperature for the exergy comparison is 5 degrees Celsius.

The heat pump is assumed to have a given performance. The operating temperature and pressure of the evaporator temperature can be raised using the heat recovered. Thus the heat pump COP can be improved based on the simple Carnot (equation 3) multiplied by a performance factor of typical exergetic efficiencies of heat pumps (Gasser, 2008). This provides an estimation of the performance increase that could be obtained in a heat pump from the reduced exergy needed to provide the high temperature lift for water heating. It shows the overall exergy used by the system with and without the heat recovery and subsequent temperature lift reduction.

**Results**

**Recovery of Wastewater Exergy**

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 2.1. The variations shown are due to complete emptying of the cooled tank, while the overflow happens only while the tank is completely full.

![Figure 2.1: Volume in the recovery tank over the course of the modeled year with the month of January highlighted.](image-url)
January is highlighted in Figure 2.1, and is shown in Figure 2.2. 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 2.2: 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.](image)

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.

![Figure 2.3: Total exergy recovered over the year versus the heat exchanger flow rate.](image)

The heat exchanger flow rate was adjusted to optimize the total exergy recovered over the year. The results indicate that a flow rate of 1.3 L/min was optimal as shown in Figure 2.3. This maximum was then checked across different tank volumes and it was found to be consistently within 0.1 L/min of this value.

![Figure 2.4: Total exergy recovered over the year versus the size of the tank for the flow rate of 1.3 L/min.](image)

The exergy output was also observed for the different values to find the optimal tank size, as shown in Figure 2.4.
In this case the output approaches a maximum asymptotically, and it follows that with a 600 L tank, greater than 95% of this maximum is achieved and is an acceptable value.

At this state the model system recovers 85 kWh (0.31 GJ) of exergy. The energy demand reported by Hendron (2007) for this hot water usage year scenario was 4800 kWh (17 GJ) and the tank model simulation gave a similar demand of 4400 kWh (16 GJ) for the year. The simulation gave a total exergy consumption for the annual hot water production of 350 kWh (1.2 GJ).

On an energy basis 3000 kWh (11 GJ) are brought out with the heat exchanger, which is 68% of the demand supplied. The amount of energy produced would increase with higher heat exchanger flow rates but the quality of the energy would go down, reducing exergy. That is why 2.3 has a maximum.

From an exergy perspective 85 kWh (0.31 GJ) are recovered compared to the 350 kWh (1.2 GJ) supplied. This is only 25% because the temperature recovered is lower than the temperature supplied, thus the exergy demonstrates the loss in quality. It is what allows for the optimization in Figure 2.3 where the exergy has a maximum. In the energy case, the energy would increase continuously with increasing heat exchanger flow rate because more heat is removed, but because the tank would decrease in temperature faster, there is less high quality energy (exergy) available.

**Exhaust Air Comparison**

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.

**Integrated Air and Water Recovery System**

It has been shown that heat recovery from wastewater is a significant potential source of exergy. Therefore it should also be integrated into high performance systems, especially those that already recover heat from exhaust air.

The recovery can be part of an integrated domestic hot water and space conditioning heat pump system. There are many options readily available (IEA Heat Pump Center, 1993). But the valuable potential shown above of exergy recovery from wastewater for use in the heat pump must be integrated. This could be optimally done by directly reducing the exergy demand of the heat pump. Ideally a heat pump with a compressor that could operate at two different temperature lifts could be designed. The heat pump could then provide low temperature lift space heating with exhaust air heat recovery, and the wastewater heat recovery could allow a low temperature lift for water heating as well. This would be done by augmenting the evaporator side of the heat pump and would have a direct impact on the COP as shown in equation 3.

**Estimated Heat Pump Savings**

A simple estimation of the increase in heat pump performance can be achieved by substituting the evaporator temperature with the recovery temperature. For a typical ground source heat pump the incoming temperature is about 10 deg Celsius. The average
temperature coming out of the heat exchanger in degrees Celsius was 15 with a maximum of 30.

For a typical exergetic efficiency of 0.4 (Gasser, 2008), the COP of a typical ground source heat pump would increase from 3 to 3.2 on average. This would decrease the electricity demand by 6%. Depending on how the dynamic heat pump system can be modulated for different inputs, the higher temperature outputs could increase performance to a COP close to 5.

Conclusions

Overall System Potential

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.

Applications

This research is part of work in the IEA ECBCS Annex 49 (www.annex49.com). The work provides the basis for the development of new heat recovery systems that consider exergy. Collaboration is underway with the large sanitary systems firm of Geberit AG, working toward eventually producing a product for market. The goal is to have a pilot project ready to be implemented in a 4 floor, 4 apartment, building project that will begin construction in 2009.

Future Work

Further analysis will include better modeling of tank stratification dynamics as well as heat exchanger characteristics. Also, a wider range of hot water usage profiles should be used to clarify how larger scale systems such as hotel and multifamily systems might function. Also, the system could be compared to a fully mixed one taking cold and hot sources. Finally, the current view of the heat pump is very simplified. Collaboration is being developed with a group to look at the real potential operation of a heat pump using the waste heat recovery scheme described. A more comprehensive model is currently being developed.

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374.
**Abstract**

The energy for water heating is often overshadowed by space heating and cooling, but as well-insulated buildings and ultimately zero energy buildings become more common, the water heating takes on a larger role in the building energy demand. A system to recover heat from warm wastewater has been studied. The analysis optimizes heat recovery using the concept of exergy in order to maximize the quantity and quality. Statistical data for hot water usage at 6-min intervals has been used to create a realistic model of heat recovery. A model assuming a recovery-tank with completely mixed conditions has been analyzed and an extension has been made to approximate a stratified tank. The optimal flow rate for the mixed tank has been found using exergy analysis of 1.3 L/min for the mixed model and 0.35 L/min for the stratified model. The energy recovered at these optimal operating conditions was 3000 kWh or 68% of the hot water demand. In terms of exergy, higher quality is found in the stratified model with 150 kWh exergy compared to 85 kWh from the mixed model. The model differences are discussed as well as the potential losses in the system.
Introduction

Zero energy buildings will never be realized unless every aspect of building energy demand is considered. Not only does each aspect have to be recognized, but also ways to integrate and optimize these systems simultaneously must be considered. This should all be done without overlooking the second law impacts of entropy production by utilizing the concept of exergy analysis.

The heating of buildings has become a focal point of research into creating zero energy buildings. Still, this focus is often limited to only space heating. But buildings are more than just warm spaces. Buildings have much in common with living organisms. They breathe air in and expel it out, materials and water come in and waste goes out, and they utilize energy to perform these among other functions. Organisms have optimized their systems over millennia, but buildings have existed for a relatively short time. This leaves much room for improvement. As organisms have done, improvements can be found by integrating the various systems, and by paying close attention to what is lost in the system that could still be used.

An area that deserves more attention is hot water production and usage. Heat recovery systems for exhaust air are becoming more common, but if the exhaust is to be recovered in a building, so should the water flow. It has significant potential for recovery. The most recent Residential Energy Consumption Survey in the United States showed that hot water production represents 17% of total energy consumption [1]. In almost every case the hot water, which has a high exergetic value, is flushed directly out of the building.

An exergy analysis has been applied to the operation of a wastewater heat recovery system. A model was used based on realistic annual hot water usage data on a 6-minute time scale. Analysis is therefore carried out such that high temperature flows on short timescales can be captured. The exergy recovery in the system is maximized for a heat exchanger operation. This exergy is used in an integrated “low exergy” building. The operation of such a system is approximated along with the potential impact of wastewater heat recovery.

A wastewater heat recovery system can be optimized to extract a maximum amount of exergy from wastewater for integration in a heat pump system as part of a low exergy building.

Background

Exergy

Exergy (Ex) is a concept that combines the first and second laws of thermodynamics. Normally the first law, which is the basis for energy balances and heat flow calculations, is used in building analysis. By incorporating the second law, a better understanding of the value of the energy being used is gained. Both the quantity and the quality are expressed by exergy. This is considered to be a better way to improve energy systems and make better energy policy [2]

Exergy is defined by adjusting the energy or heat, Q, by a term representing the change in entropy, As relative to the external environmental conditions with temperature T₀. This is given in Equation 1 [3].
In order to calculate the exergy change for water flows one assumes an incompressible fluid with mass flow rate, \( \text{mdot} \) and a constant specific heat at different temperatures, \( c_p \). The entropy term is estimated using the natural logarithm of the ratio of the temperature change from hot to cold in the fluid, \( T_H/T_C \). This provides the exergy change in the water flow, \( E_x \), as shown in Equation 2 [4].

\[
E_x = \text{mdot} \cdot c_p \cdot [(T_H - T_C) - T_0 \ln(T_H/T_C)]
\]  

(2)

If only the energy in water or air is of interest, it can be calculated based on the temperature and properties of the substance alone. The result is an absolute amount. In the case of exergy, the relative quality of the external environment is also considered in the analysis. The actual potential of the energy available to perform useful work within the relative surroundings of the system can thus be determined. The relative surroundings are accounted for by the reference state including the reference temperature \( T_0 \). In this way the loss of quality is revealed by the exergy lost in the use of high temperature systems relative to their environment and in heat exchanges across large temperature gradients [2,5].

The definition of the external environment, \( T_0 \), is fixed for most systems operating in controlled environments, but for large scale systems like buildings it can be assumed to be fixed for individual systems, or it can be taken to be the outside conditions. For steady state analysis of heating systems or cooling systems this can be the value for the design performance criteria for that climate [4,7].

Another term that is often used along with exergy is anergy. This refers to exergy that has been destroyed or is at the environmental state. It can no longer do work relative to the defined environment, and therefore another name for the environmental state is the dead state. Although work cannot be created from this state, work can be done in a thermodynamic cycle to extract anergy from the dead state as is done by heat pumps. Anergy is also used to quantify the amount of exergy destroyed in optimization problems.

**Low Exergy Buildings**

Buildings require only low temperatures for comfort so high temperature combustion sources are not needed. In general exergy analysis tells us that large temperature gradients in any system should be avoided.

Buildings that are considered to have low exergy systems utilize the concept of low temperature heating and high temperature cooling. This minimizes the temperature gradient between the room air and the heat source, thus minimizing exergy destruction. In order for adequate heating or cooling to be supplied, usually a large surface area is needed as in the case of TABS or chilled beams, while also maintaining a well-insulated envelope that minimizes the heat flow. This allows small temperature gradients to supply adequate conditioning. An extensive overview is found in the IEA Annex 37 Guidebook [6] along with introductory exergy material at www.lowex.net, and is being further developed in the IEA ECBCS Annex 49.

In this project an important feature of a low exergy building is how well suited it is for heat pump applications. Heat pumps can provide both low temperature heating and high temperature cooling, and by doing so achieve their maximal efficiency. But in these systems hot water must still be produced at a higher temperature. Therefore, it is very interesting to find ways to augment the efficiency of the heating process such as through wastewater heat recovery.
Heat Pumps

The laws of thermodynamics allow a heat pump to transport a certain amount of heat per unit of work input into the system. This performance (heat moved per energy input) is the coefficient of performance (COP) and it has a theoretical maximum defined by a reversible Carnot cycle given in Equation 3 [4].

\[
COP = \frac{T_H}{T_H - T_C} \quad (3)
\]

A real heat pump has a COP less than the maximal Carnot COP due to losses in the system. Still, it is clear that the potential of heat pump performance is dependent on the temperature lift it must provide. The exergetic performance of heat pumps has been extensively studied [8,9,10], and shows the potential for better optimization of heat pump systems through the use of exergy analysis.

The use of heat pumps for the production of hot water is well known [11]. The application of heat pumps for hot water production is expanding as fossil fuels become more costly [12]. New methods of measuring seasonal efficiency of integrated hot water and space conditioning heat pumps have been developed [13]. Increasing the source temperature of heat pumps \(T_C\) with a high exergy source such as wastewater will increase the heat pump performance [8].

Domestic Hot Water Usage

Most hot water usage is found in domestic systems, with the most concentrated usage found in large hotels or apartment complexes. In order to realistically consider the potential of using energy from hot wastewater, one must consider how and when hot wastewater is produced. Unlike ventilation, the usage is sporadic and unpredictable [14]. For an accurate look at the recovery of exergy from this system, realistic usage must be considered [15].

Methods

Data Acquisition

The data used for the simulation of the hot water usage came from a probabilistic simulation engine developed at the University of Kassel [16]. This engine was used to produce usage profiles based on statistics gathered at the US National Renewable Energies Laboratories (NREL). The data was produced from the engine based on usage profiles for showers, baths, sinks, laundry, and dishwashers for a typical year [17]. Each usage type was generated based on statistics from survey data for profiles of a two, three, or four bedroom residence. The software generated a random set based on the statistical distributions of hot water events on a 6-minute time scale for an entire year. The output includes data for pure hot consumption or for the hot-cold mixes of baths, showers and sinks. The temperatures of the usage are taken from [17]. The data for four bedrooms was used to model the wastewater heat recovery tank, and the entire year was compiled into one input for the models created in Matlab.

3.2 Mixed Tank Model

The simulation uses the flow of hot water over time along with its temperature from the data mentioned above, and it sends hot water to a recovery tank with a set diameter, volume, and wall heat transfer coefficient. The tank contains a heat exchanger having a flow rate, fixed supply temperature of 10°C, and pipe diameter, and is shaped in a spiral. The
spiral width is sized relative to the tank diameter, and the spacing between turns is relative to the pipe width.

At each time step the simulation checks if a hot water event occurred and the amount of water going into the tank. The temperature of the incoming water is according to [17] and the losses during flow to the tank and losses during usage are subtracted. These are estimated to be 5, 3, 2, 5, and 2 percent for bath, shower, sink, clothes and dishes respectively.

If an event has occurred, the new volume of the tank is calculated. A valve is simulated that activates if the tank fills to capacity. It removes liquid from the bottom of the tank, so if the new volume is greater than the capacity, the previous water is removed to make space for new input.

New events are combined using an energy balance with the current volume in the tank. This calculates the new temperature of the tank assuming it is completely mixed. The heat extraction by the heat exchanger is modeled as a laminar flow through a pipe with constant surface temperature equal to the tank temperature [18]. The heat extracted from the tank and the heat losses from the walls are calculated at each step using an energy balance to determine the new temperature. This provides the temperature of the tank for the next time step. If the temperature has dropped below a set point above the inlet temperature of the heat exchanger the tank is flushed completely and waits for the next event.

**Stratified Tank Model**

A second model was derived that allowed for an approximation of a tank with stratified conditions. The same setup for the input of data was used in the mixed model. In this case the wastewater volume is broken up into discrete layers within the tank. The heat exchanger is modeled using the same equations only the heat is removed separately from each layer during each time-step. Because the heat exchanger flows in from the bottom, the heat is removed there first creating a stratified state. Thus the temperature at the top stays warmer and the output temperature of the heat exchanger at the top is higher (more exergy). The conduction between each layer is included as the stratification develops, and the temperature differences are monitored such that unrealistic extreme cases can be avoided. In this case a valve is simulated that would be at the bottom of the tank and empties the bottom layers that drop below a set temperature at each time step. The tank is also emptied at its maximum fill as done in the mixed model.

**Exergy and Energy Analysis**

At each step the amount of exergy available from the wastewater is calculated from Equation 2 and amount of heat extracted by the heat exchanger is calculated from an energy balance. The reference state for the exergy comparison is 1 atm and 5°C. The optimal heat exchanger flow rate and tank size are probed, and the relative amount of heat recovered is determined.

The heat pump is assumed to have a given performance providing 55°C hot water. The operating temperature and pressure of the evaporator temperature can be raised using the heat recovered. Thus the heat pump COP can be improved based on the simple Carnot (Equation 3) multiplied by a performance factor of typical exergetic efficiencies of heat pumps [8]. This provides a rough estimation of the performance increase that could be obtained in a heat pump from the reduced exergy needed to provide the high temperature
Exergy recovery from warm wastewater for an integrated low exergy building system

lift for water heating. It shows the overall exergy used by the system with and without the heat recovery and subsequent temperature lift reduction.

Finally the application of the system is considered by estimating the pumping cost and the running time of the exchanger system.

**Results**

**Mixed Tank Model**

The dynamic filling and emptying of the 400 L recovery tank for each 6-minute time step over the model year is shown in Figure 2.5. The variations shown are due to complete emptying of the cooled tank, while the overflow happens only while the tank is completely full. January is highlighted in Figure 2.5, and is shown in Figure 2.6. In Figure 2.6 the top plot shows the total volume given in Figure 2.5 with better resolution, as well as the overflow volumes for the cases where the tank is filled to capacity and dumps an overflow amount, shown in black. The bottom plot is the tank temperature. The temperature decreases quickly after each fresh input to the tank, and then decreases slowly until it is emptied.

![Figure 2.5: Volume in the recovery tank over the course of the modeled year with the month of January highlighted](image)

A normal fill and recovery cycle appear to take about one to two hours as shown in Figure 2.6. The exergy recovered follows the tank temperature as expected. The maximum amounts of exergy being extracted are about an order of magnitude greater right after events than what is extracted at steps when the tank has not had a recent event.

![Figure 2.6: 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.](image)

The heat exchanger flow rate was adjusted to optimize the total exergy recovered over the year. This revealed an optimal flow rate of 1.3 L/min as shown in Figure 2.7.

The maximum was then checked across different tank volumes and it was found to be consistently within 0.1 L/min of this value. The exergy output was also observed for the different tank volume values to find the optimal tank size. This varied slightly for different time periods and models, but 400 L provided a maximal output or at least above 90% of the maximum in various simulations. Other parameters of the heat exchanger, such as pipe diameter and spacing were varied but the impact was not as significant.
Figure 2.7: Total exergy recovered over the year versus the heat exchanger flow rate.

At this state the model system recovers 85 kWh of exergy. The energy demand reported by [17] for this hot water usage year scenario was 4800 kWh and the tank model simulation gave a similar demand of 4400 kWh for the year. The simulation produced total exergy consumption for the annual hot water production of 350 kWh.

On an energy basis 3000 kWh are extracted with the heat exchanger, which is 68% of the demand supplied. The losses are just the energy that is flushed down the drain, and on an energy basis they can be reduced by simply increasing the flow rate and removing more of the heat before it is flushed. 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, and thus an example where exergy shows a loss in quality that would not be captured by energy analysis alone. It is what allows for the optimization in Figure 2.7 where the exergy has a maximum. The energy increases continuously with increasing heat exchanger flow rate because more heat is removed, but because the tank would lose its temperature faster, there is less high quality energy, and thus exergy available.

Stratified Tank Model

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 2.8.

Figure 2.8: 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 the 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, the lower rate 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 rate gains 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.

**Estimated Savings and Costs**

A simple estimation of the increase in heat pump performance can be achieved by substituting the evaporator temperature where the heat pump receives its heat with the recovery temperature from the wastewater. For a typical ground source heat pump the incoming temperature is about 5-10°C. The average temperature coming out of the heat exchanger is 15°C with a range going up to 30°C (Figure 2.6).

For a typical exergetic efficiency of 0.4 [8], the COP of typical ground source heat pumps would go from 2.6-2.9 to 3.3 for the average supply of 15°C. Depending on how the dynamic heat pump system can be modulated for different inputs, the higher temperature outputs could increase the COP to close to 5.

Nevertheless, this project is focused on heat recovery from wastewater, where the heat recovered could be used for a variety of systems. Here the primary idea is on the integration of a heat pump where the high quality energy in the form of exergy can be best utilized as calculated above. Still, the integration with a heat pump would influence the operating parameters, and as an integrated system the optimization could be different. The COP calculations above are rough estimates. In collaboration with the Lucerne University of Applied Sciences and Arts the heat pump analysis will be extended to include its influence on performance, and the system will be tested in an experimental setup, providing more reliable heat pump results.

The additional operating costs of the system also must be estimated. They would consist of the heat exchanger pumping costs along with any maintenance costs. In this case a rough estimate of the pumping was on the order of a few Watts. The pumping power at these flow rates is miniscule, making the cost in this case insignificant. Still, further optimization incorporating the heat pump operation may show an increase in pumping demand of the system, although it is not likely to be dramatic.

**Conclusions**

**Overall System Potential**

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 when a mixed tank is modeled, and 145 kWh when a stratified tank is modeled. This is for 3000 kWh or 68% recovery of hot water heat, and is for flow rates of 1.3 L/min and 0.35 L/min for the mixed and stratified models respectively. A potential concept for integration of this system is presented, and an estimate is made of the performance increase in the heat pump during recovery. The average increase in performance of more than 10% has a potential to nearly double if the higher temperature heat recovery outputs can be utilized. This could
significantly reduce the primary energy demand for hot water supply in low exergy buildings.

Applications

This research is part of work in the IEA (International Energy Agency) ECBCS (Energy Conservation in Buildings and Community Systems) Annex 49 (www.annex49.com). The work provides the basis for the development of new heat recovery systems that consider exergy. Collaboration is also underway with the largest sanitary systems firm in Europe, Geberit AG, They will use the theory and concept developed here to eventually produce a product for market. The goal is to have a pilot project ready to be implemented in a 4 floor, 4 apartment, building project in Zurich that will begin construction in 2009. The expense of installation of such a system will include the cost of the tank, the heat exchangers between the tank and the heat pump, and any piping required. The cost should not create a barrier to implementation, but the payback would have to be detailed in order to convince people to make the investment. Finally, this system is ideal for use in conjunction with grey water systems as these naturally handle the warm wastewater sources and the large cold wastewater sources (i.e. toilets) discreetly. The reduction in overall water usage combined with the reduction in energy demand make a good integrated system.

Future Work

Further analysis will include improved modeling of tank stratification dynamics as well as heat exchanger characteristics using better approximations of the system. It will include finite difference analysis for the transient temperatures between time steps and also a CFD analysis of the tank. Also, a wider range of usage profiles should be used to understand how larger scale systems like multifamily and hotel systems might function. The system could be compared to a fully mixed one taking cold and hot sources, as well as to a simple analysis of the pass-through heat exchangers used to pre-heat the cold-source input of shower water. Finally, the current view of the heat pump is very simplified. The pumping costs and equipment costs for integration into the heat pump system will be considered in detail in the future. The collaboration with the Lucerne Univ. of Applied Science and Arts will lead to a more realistic evaluation of the integration with the heat pump, both analytical and experimental. It will lead to a better understanding of the real potential operation of a heat pump using the waste heat recovery scheme as described for single to multi-family residence scales.

References

Exergy recovery from warm wastewater for an integrated low exergy building system


Abstract
As a part of the broader theme of low exergy (LowEx) buildings, this project has analyzed the utilization of both energy and exergy from the wastewater stream of buildings. It demonstrates the potential of wastewater heat recovery. A realistic model of annual hot water usage for different sizes of residential structures reveals the potential to recover about 90% of the energy in wastewater when the system is optimized using exergy analysis for maximal exergy recovery. At these operating points, and by using an integrated renewable ground source heat pump, savings of upwards of 500 CHF per year and more than 1 ton of CO2 per year are achieved compared to a standard electric boiler.

The project is a part of the Swiss Federal Office of Energy funded Swiss participation in the IEA ECBCS Annex 49, “Low Exergy Systems for High Performance Buildings and Communities.” The system has been modeled and will be used as the basis of a Swiss OPET CTI collaboration with Geberit International AG to bring a wastewater heat recovery product quickly to market.

The highest performance is only achieved through complete integration with the low exergy building system. By using low temperature heating with activated thermal mass, a very high heat pump performance is achieved for space heating. This “low-temperature-lift” high performance of the heat pump is extended to water heating by integrating the wastewater heat recovery. Potential realization of the complete system in the ViaGialla B35 building project in Zurich (www.viagialla.ch) will also be described. The project will be the pilot project for many advanced LowEx technologies including heat recovery and planning is nearly complete with construction set to begin in July 2009.
Exergy and building systems: full potential of heat recovery

Introduction

Buildings provide one of the fundamental needs of humans: shelter. But modern buildings go much beyond simply providing shelter from the outdoor environment; they also create a comfortable indoor environment that meets very specific demands. The expanded demands on buildings have led to the growth of their energy consumption as they have become more comfortable, more functional, and more spacious, now demanding around 2/3 of all the electricity produced in the world [1]

By now the negative impacts of this growth have been recognized with upwards of half of global greenhouse emissions being caused by the building sector [2,3]. Our modern built environment has only existed for a few hundred years, which leaves room for much needed improvements. One area that has hardly been considered is the potential benefits of heat recovery from the warm wastewater. In cold climates the largest demand by far is for heating, and even in temperate and mild climates heating can be the largest energy demand due to water heating.

Figure 2.9: As building performance levels increase the focus is primarily on space heating because it was the largest part in the beginning, but now further advancements must start to address the issue of warm water energy demand.

A person typically uses approximately 100 to 200 L of water per day, more than half of which is usually hot water [3,4]. Most studies focus on the usage amount for supply and tank sizing, which makes it easy to overlook the energy demand. The actual energy demand for hot water is typically around 2000-4000 kWh per year per household or about 20-40 kWh per year and per m² of building floor space [5,6,7]. Reasonable estimates are available for the total demand from state and national energy reports [7], but these have no indication of how hot water demand could be reduced in system designs. The reductions are important because as buildings have become more efficient hot water demand has become a much more significant portion of the overall demand. This is illustrated in Figure 2.9
comparing the space heating, appliance load and the water heating energy demands for various levels of building performance.

Furthermore, building hot water systems provide a very valuable energy flux that is also energy-dense. Water has a large heat capacity and warm water used in a building is at a relatively high temperature. The largest hot water usage, being showers, is usually at least 40°C. This means that warm wastewater can have a very high potential value if recovered.

The concept of exergy allows us to better quantify this extra value. We can optimize the recovery of heat using exergy analysis to maximize the performance of the heating system.

For high performance buildings it is again even more significant to consider the exergy in wastewater. Figure 2.10 demonstrates that as building water systems achieve higher performance levels, and in this case are also more ecological, the makeup of the wastewater becomes more valuable. Therefore better buildings should address the potential of wastewater heat. By combining the need for reduced hot water energy demand with a system based on exergy analysis, an optimized wastewater heat recovery can be designed. The hot water demand is then made much smaller while still meeting the need for comfort and functionality.

![Figure 2.10: Exergy available in building wastewater streams. Better buildings have a higher fraction of warm wastewater for recovery.](image)

**Methods**

In order to analyze the potential recovery of heat from a building wastewater stream, the first step is to generate a realistic data set for the stream. A statistical domestic hot water software tool (DHWCalc from The University of Kassel) [8] was used to generate one year of hot water events with a 6-minute time interval. 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 [9,10]. With this data the warm wastewater
Exergy and building systems: full potential of heat recovery

flow can be estimated. One major assumption is that of the temperature of the wastewater. A conservative value of 30°C was used to account for cold water mixing and transit losses.

The design assumptions included a spiral pipe that was coiled inside of the tank to capture the wastewater. The working fluid for heat exchange was water and it was assumed to enter with a temperature of 12°C. This was chosen because it was slightly warmer than usual ground source heat pump evaporator temperature that could use the recovered heat. The tank size and heat exchanger length were varied in the analysis as well as the heat exchanger flow rate.

An energy balance was performed on the system at each 6-minute time-step. 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 1 determined the outlet temperature, $T_{out}$, of the heat exchanger at each time-step based on the current tank temperature, $T_{\infty}$, the entering water temp, $T_{in}$, and the properties of the system (density, $\rho$; 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 diameter, $D_{pipe}$).

$$T_{out} = T_{\infty} - e^{-h_{fluid} \pi D_{tank} L_{tank} \rho \rho Q c_p \left( T_{\infty} - T_{in} \right)}$$

where $h_{fluid} = Nu \frac{k}{D_{pipe}}$.

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 2 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, $T_{in,HX}$.

$$Ex = Q_{out} - T_{env} \ln \left( \frac{T_{tank,ave}}{T_{in,HX}} \right)$$

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. It was done by evaluating the potential improvement to the COP based on Equation 3 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. A comparison can then be made to traditional heating systems.

$$COP = \left[ \frac{T_{Supply}}{T_{Supply} - T_{Available}} \right]$$
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-CO₂/kWh and for natural gas combustion it is 0.25 kg-CO₂/kWh.

Results

The potential annual recovery of energy and exergy were calculated, and Figure 2.11 shows how the exergy analysis provides a unique optimization point that is not shown in the energy analysis.

![Figure 2.11: Plot of the exergy and energy recovery for different HX flow rates (left) and tank sizes (right). There is a clear optimum in the exergy analysis not given by the energy analysis.](image)

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. Figure 2.12 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 2.12: Tank Size exergy recovery optimization for different sizes.](image)

The savings are about 1500 kWh per year per residence, which assumes an input of about 3000 kWh per year for hot water at 50°C, and a wastewater temperature of 30°C. That translates to about 1,700 kWh per year available to recover. A 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.

Recovery values translate 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, \( \eta_{\text{Carnot}} \). 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.

Discussion

The wastewater heat recovery (WRG) system shows great potential for energy savings, cost reduction, and environmental benefit. The type of operation influences the performance benefits. The direct use of the recovered heat to preheat water would be a cheaper installation than an integrated heat pump system. But the other benefits in the operation of an entire building when installing a low exergy high performance heat pump system are great.

The final design will be further optimized in collaboration with Geberit International AG. This analysis provides an initial look at the system feasibility, and how exergy analysis can be used to optimize the system. The exact recovery could vary considerably depending on the average temperature of the wastewater stream. In this case a very conservative estimate of 30°C was used, and for recovery directly after a shower the temperature could be much higher.

The pilot system will be integrated into the B35 building project in Zurich. It will combine a low exergy ground source heat pump system that minimizes the temperature lift that the heat pump provides for all space heating and water heating. This will be done through a combination of exhaust heat recovery and wastewater heat recovery. By using the wastewater heat recovery, a relatively low temperature lift can be maintained for all parts of the heat pump heating system, including for hot water. Not only that, but the hot water is planned to be distributed at a lower temperature around the temperature of a shower (the most common use). Decentralized electric heaters will provide the smaller amounts of hotter water that are needed. The overall gain in performance from the temperature reduction should outweigh the small decentralized electric demand. One future goal is to make it possible for these decentralized heaters to operate on the basis of a heat pump. The system is currently in the final planning phases, and construction is set to begin in 2010.
Acknowledgements
Swiss Federal Office of Energy, IEA ECBCS Annex 49

References

Keywords: Heat recovery; water heating; hot water; wastewater; heat pump; exergy

Abstract

There is a large potential in the heat losses from the wastewater leaving a building. We present a novel concept for recovering this heat. Instead of recovering it in a mixed state, the recovery immediately after use is evaluated. This allows the exploitation of the higher temperatures found at the points of warm water usage. By integrating a heat pump to utilize this heat, we can produce a higher temperature heat supply while maintaining a low temperature-lift requirement. This leads to the possibility of directly regenerating the hot water supply through wastewater heat recovery. The concept is a result of research into low exergy building systems, and is part of the IEA ECBCS Annex 49. We have modeled the annual performance of two different system scenarios, which result in a potential average annual coefficient of performance (COP) of over 6. The first scenario supplies up to 4,400 kWh of heat for all hot water events with only 790 kWh of electricity, while the second scenario regenerated directly the hot water supply just for bathroom fixtures at 2400 kWh with just 410 kWh of energy. This is a significant reduction in the demand for hot water supply of a building compared to most modern installations.
### Nomenclature

**Symbols**
- IEA: International Energy Agency
- ECBCS: Energy Conservation in Buildings and Community Systems
- COP: coefficient of performance
- DHW: domestic hot water
- En: energy (J)
- Ex: exergy (J)
- Q: heat (J)
- W: work (J)
- t: time (seconds)
- T: temperature (K)
- V: volume (m³)
- UA: overall heat transfer coefficient (W/m² K)
- cp: specific heat capacity (kJ/kg K)
- rho: density (kg/m³)

**Indexes**
- empty: signifies a point where the recovery tank empties
- old: signifies a value from a previous event
- new: signifies a value from a new event
- add: signifies an input value
- in: signifies a value for inside
- out: signifies a value for outside
- hx: heat exchange value
- o: value for the dead state
- h: signifies the hot value
- c: signifies the cold value
- ave: average value
- demand: demanded by the system and must be supplied
- supply: the value supplied by the system
- mains: value for the input from the municipal water
**Introduction and Background**

There is a great impetus to change the way buildings are designed and built. At present, the building sector is directly or indirectly responsible for around half of global greenhouse gas emissions when considering the construction, maintenance and operation of buildings [1]. Buildings are responsible for the consumption of two-thirds of all electricity produced and one-third of global waste production [2]. This impact can be reduced by either increasing the sustainability of the energy supplied through increased renewable supply, or by decreasing the demand through improved building performance. There have been significant strides in reduction of demand through increased efficiency in recent years, but the primary focus has only been on heating and cooling systems. Hot water supply is often overlooked. It is becoming common for high performance buildings to be extremely airtight and well insulated, and to have systems such as exhaust ventilation heat recovery. These buildings, such as Passivhaus designs with less than 15 kWh/m²a of heat demand [3], have very low space heating demand, but there remains a significant hot water demand in the range of 50 kWh/m²a [4]. In this study, we present a new method to potentially reduce energy demand by reducing the energy required to supply hot water.

When we observe the ratio of hot water energy demand compared to space heating and other sources as shown on the left of Figure 2.13, it is usually only 10-20% for typical house from the late 20th century [4]. But as we move to more high performance buildings, we see that the hot water heat demand is rarely impacted by improvements in performance, and it becomes a significant, if not a major, fraction of the demand [3].

![Figure 2.13: Hot water energy demand and exergy potential. Illustration of the significant increase in the hot water fraction of total energy demand for buildings as building performance increases (left) [3-4], as well as the increasing quality of wastewater as improved sanitary installation are used (right) [5-7].](image)
Not only is hot water a significant demand, but the wastewater flow also has an exergetic value as shown on the right in Figure 2.13 [5-7]. Water has a high heat capacity and density, so wastewater provides a concentrated source of heat. Also, hot water usage is at a high temperature, in the range of 40-50 °C. By using exergy analysis, the appropriate value can be given to heat sources like wastewater, which considers the value and potential of their temperature and not just their relative quantity of energy [8]. This leads us to the development of integrated systems that minimize temperature gradients and temperature losses, and thus exergy and not just energy losses, which facilitates the minimization of the building system primary energy demand [5,6]. A comprehensive review of such systems is available [9], and methods for application of exergy analysis for building systems have been reviewed [10], and presented in case studies [11], including exergy analysis of hot water production with heat pumps [12].

In this study we demonstrate the potential of integrating a heat pump directly into the heat recovery from wastewater. Past studies have shown a significant potential of grey water heat recovery [7], and also how a significant amount of energy and exergy can be recovered from wastewater [13,14]. This high temperature recovery integrated with heat pump operation has the potential for increased performance that can be missed in large-scale centralized systems that are based on energy analysis alone [15,16], because the exergetic value of the source temperature is recognized. For example, large-scale installations of heat recovery from municipal sewers [15] may capture the same energy flux leaving buildings, but it does so at a much lower temperature than the hot water usage temperature. Instead of just recovering waste energy, we exploit the waste exergy, which incorporates the value of higher temperatures, and we can maximize the potential of this exergy with a heat pump.

Figure 2.14: 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 [5,6].

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The ability of a heat pump to operate with high performance is illustrated in Figure 2.14. The coefficient of performance (COP), which is the ratio of heat delivered to energy demand (usually electricity input for residential heat pumps), is dependent on the difference between the temperature of the heat source from which the heat pump acquires heat and the temperature at which the heat pump supplies heat to the building, otherwise known as the temperature-lift. As the temperature-lift drops below 20 K the COP increases rapidly as discussed in [5,6], reducing the energy demand.

Figure 2.14 demonstrates how low exergy building systems strive to reach performance levels that result in temperature-lifts for the heat pump below 20 K and a COP above 8 [5,6]. For space heat and cooling, this can be achieved with properly designed low temperature heating and high temperature cooling systems as described in the IEA ECBCS Annex 37 [18]. The higher temperatures needed for hot water supply make achieving a low temperature-lift more difficult. Existing systems utilize exhaust air as higher temperature source for domestic hot water heat pumps [19], but this is limited in power and the temperature-lift is still between 20 and 40 K. As part of our contribution to the IEA ECBCS Annex 49 [20] we developed this concept to minimize the temperature-lift for heat production at a temperature capable of producing hot water.

Methods and Analysis

System Overview

The system we have devised is a simple heat recovery tank that accepts the outgoing warm wastewater. This could be connected, for example, to the shower/bath and clothes washer in a typical home. It could also be easily incorporated into a grey-water recycle system that accepts all warm waste flows in a high performance building as shown on the right of Figure 2.13. In any case, we want to include the potential separation of warm sources from the cold source of toilets so we can observe the highest potential performance.

The recovery tank accepts the wastewater and a heat exchanger supplies the heat to the heat pump. The heat pump lifts the temperature of the recovered heat to a sufficient level to generate new hot water. The heat pump performance is dependant on this temperature-lift, and at lifts below 15 K, more than 10 units of heat can be moved with one unit of energy input [17], thus operating with a coefficient of performance (COP) of more than 10.

Input Data Sources

The modeling of wastewater heat recovery presents several obstacles. First, appropriate input data has to be generated or acquired based on highly variable water usage statistics. Because wastewater heat is almost never considered, there are no statistics available for temperature and output of the wastewater itself. Therefore the model must depend on data for hot water usage, and then calculate a subsequent wastewater output.

The hot water usage statistics often lack the resolution or characteristics necessary to properly evaluate the potential to recover the wastewater. For the recovery, it is necessary to accurately produce an event time and duration so that the recovery can be accurately modeled for multiple events throughout the year. This requires data for the sources of water usage and their temperature, duration, and flow rate. Most of this type of data is available for solar hot water system design and modeling [21]. There is some niche software available for producing hot water event schedules, which was used in some previous work.
The potential of wastewater heat and exergy: decentralized high-temperature recovery with a heat pump

[22]. The input for our model used a dataset that was generated by the National Renewable Energy Laboratory (NREL) [23].

The input data was available for the annual use of baths, showers, sinks, clothes washers and dishwashers for a typical 2-bedroom, 3-bedroom, or 4-bedroom home. The data accounts for typical annual load profiles of the events as well as statistical probabilities of clustered events, such as showers in the morning. This is important to consider for the heat recovery during higher usage periods like the morning.

This model is a new version, which unlike previous versions [13, 14], is not based on a dataset with fixed time-steps. Instead of having a continuous time variable on the order of a few minutes for the entire year, the events are modeled with a time stamp, duration, flow-rate and fixture-type. This smaller dataset allows each event to be modeled in a single iteration and allows events for various fixtures to be more easily filtered out.

**Heat Recovery Model**

The setup for the heat recovery system has been upgraded from previous work [13, 14] to use a tank with the heat exchanger installed in the walls. This was selected rather than the spiral heat exchanger immersed in the fluid due to the potential problems with bio-film buildup, and the goal of facilitating a cleaning function. The heat capacity and density, $c_p$ and $\rho$ respectively, are assumed to be standard values for water, 4.2 kJ/kgK and 1kg/L respectively. This tank design required a range of heat transfer coefficients for water in a cylindrical tank to be considered. These were determined using standard free convection models for the range temperatures used in the model [24]. These ranged from about 50 to 200 W/m²K.

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, [17].

**Recovery Model Independent of DHW Demand**

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, $t_{\text{empty}}$, that it would take the tank to empty. This is calculated from Equation 1 with a selected tank emptying temperature, $T_{\text{empty}}$, by using an energy balance based on the old temperature, $T_{\text{old}}$, the fixed temperature gradient between the wastewater and the recovery fluid, $\Delta T_{\text{hx}}$, the overall heat transfer coefficient, $UA_{\text{hx}}$, and the tank volume, $V_{\text{old}}$. 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 2 and 3 where $T_{\text{in}}$ is the initial temperature of the tank and $T_{\text{out}}$ is the emptying
temperature of the tank, $T_{\text{empty}}$. If the time, $t_{\text{empty}}$, is greater than the time since the last event, $t_{\text{event}}$, then it is still extracting heat from a previous event when the next event occurs. In this case, the new partially cooled temperature, $T_{\text{new}}$, of the previous event is calculated based on the heat extracted since it was added to the tank using Equation 4. Also the energy, $E_n$, and exergy, $E_x$, extracted are recorded since the event was added, again from Equation 2 and 3.

The new temperature, $T_{\text{new}}$, of the old event is then used to determine the new combined temperature of the tank, $T_{\text{tank}}$, using the energy balance in Equation 5, where $V_{\text{old}}$ is the new volume added to the tank and $V$ is the actual volume total for the event, in this case the combined total.

\[
(1) \quad t_{\text{empty}} = T_{\text{old}} - T_{\text{empty}} \cdot c_p \cdot \rho \cdot V_{\text{old}} \cdot (\Delta T_{\text{hx}} \cdot U_{\text{hx}})
\]

\[
(2) \quad E_n = c_p \cdot \rho \cdot V \cdot (T_{\text{in}} - T_{\text{out}})
\]

\[
(3) \quad E_x = c_p \cdot \rho \cdot V \cdot (T_{\text{in}} - T_{\text{out}} - T_0 \cdot \log(T_{\text{in}} / T_{\text{out}}))
\]

\[
(4) \quad T_{\text{new}} = T_{\text{old}} - \Delta T_{\text{hx}} \cdot U_{\text{hx}} \cdot t_{\text{event}} / (c_p \cdot \rho \cdot V_{\text{old}})
\]

\[
(5) \quad T_{\text{tank}} = (T_{\text{in}} \cdot V_{\text{add}} + T_{\text{new}} \cdot V_{\text{old}}) / V
\]

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, $Q_c$, calculated in Equation 6, is constant throughout each event because of the constant recovery tank heat exchange temperature difference, $\Delta T_{\text{hx}}$ and the constant overall heat transfer coefficient, $U_{\text{hx}}$, based on the free convection models [24] and surface area from the tank volume and geometry. The total energy recovered, $Q_c$, is also dependent on the time, $t$, of recovery, which is either the time it takes to empty the tank, $t_{\text{empty}}$, or the time between events, $t_{\text{event}}$, in the case that there is an overlap. The COP is a ratio of higher temperature heat supplied, $Q_h$, 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, $\Delta T$, as in Equation 7. We have fixed the warm heat pump supply temperature, $T_w$, so the only time-dependent variable is the cooler evaporator temperature, $T_c$, for recovery, which can be defined linearly as above in Equation 4 for $T_{\text{new}}$. 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, $COP_{\text{ave}}$, over that time period, Equation 8.

\[
(6) \quad Q_c = \Delta T_{\text{hx}} \cdot U_{\text{hx}} \cdot t
\]

\[
(7) \quad COP = Q_c / W = g \cdot T_{\text{in}} / (\Delta T) \text{, where } \Delta T = T_{\text{in}} - T_c
\]

\[
(8) \quad COP_{\text{ave}} = g \cdot T_{\text{in}} / k_1 \cdot \left[ \log(T_{\text{in}} - T_c + k_1 \cdot t) - \log(T_{\text{in}} - T_c) \right] / t \text{, where } k_1 = (\Delta T_{\text{hx}} \cdot U_{\text{hx}}) / (\rho \cdot V \cdot c_p)
\]

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 9 and 10.

\[
(9) \quad W = Q_c / (COP_{\text{ave}} - 1)
\]

\[
(10) \quad Q_h = COP_{\text{ave}} \cdot W
\]
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 11. 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 \[18\]. With this calculation we can then compare the potential recovery of heat using the heat pump to the heat supply, \(Q_{\text{demand}}\), that would be demanded for the actual hot water being used based on the volume added at each event, \(V_{\text{add}}\), the temperature of each supply event, \(T_{\text{supply}}\), and the mains temperature, \(T_{\text{mains}}\).

\[
Q_{\text{demand}} = c_p \cdot \rho \cdot V_{\text{add}} \cdot (T_{\text{supply}} - T_{\text{mains}})
\]

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, \(T_{\text{empty}}\), 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.

**Recovery Model Connected to DHW Demand**

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, \(T_{\text{empty}}\). 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, \(Q_h\), is matched to the heat demand for hot water supply, \(Q_{\text{demand}}\). 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 11, equal to the heat supply, \(Q_h\), Equation 8, 9 and 10. 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 \[24\], 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.

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, $T_{\text{empty}}$. This temperature was varied from 15-30°C. 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, as shown in Figure 2.15, 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 2.15. Performance for varying emptying temperature. The heat recovery and COP are plotted on two axes 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 2.15 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 2.16 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 2.15. The analysis of the exergy recovery from the tank [13,14] allowed us to initially observe the higher potential of decentralized wastewater heat recovery, and to subsequently connect a heat pump to the system to take advantage of this potential.

Figure 2.16: Energy and exergy comparison. Plot of energy recovered, also depicted in Figure 2.15, 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 [19]. For example when the tank is emptied around room temperature, at 20 °C, a heating demand of 3300, 3800, 4400 kWh/a was provided with a heat pump demand of only 550, 690, and 790 kWh/a 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/a [4]. These relatively small electricity demands facilitate the combination with other renewable systems, such as photovoltaics, which can more easily supply this amount of electricity. At these COP levels, any PV panel with an efficiency of greater than 18% can supply more than 100% of the solar energy as heat, clearly outperforming any solar thermal system.

This analysis assumes 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 [6].
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 result was for a rather conservative value of the recovery tank heat transfer coefficient, which leads to a longer recovery time for each wastewater heat recovery event, increasing likelihood of overflow events and required tank size. 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 2.17 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 2.17: 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 2.17. More importantly, the realistic datasets and modeled operation demonstrate the potential for a performance 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
The potential of wastewater heat and exergy: decentralized high-temperature recovery with a heat pump

...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/a 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/a 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.

**Figure 2.18**: 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.

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 2.18.

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 2.19 shows the number of times per year that the supply tank of hot water runs out of water. A tank of about 400-500 L was found adequate to minimize these events to less than 10 per year for 2, 3 and 4 bedroom datasets.

**Figure 2.19**: 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 2.20 shows the dependency of the heat pump work and COP on heat transfer performance. This was done for the optimized tank dimensions.

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.

Another important aspect of the system operation is the relative time frame of operation 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 of 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.

Figure 2.20: 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.

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 [25] based on the results of a previous study [14], 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.

**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/a per number of bedrooms in the household. For the 4 bedroom household the, bathroom hot water heating demand of 2400 kWh/a was met with just 400 kWh/a 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.

References

The potential of wastewater heat and exergy: decentralized high-temperature recovery with a heat pump


Chapter 3

3 Active Low Exergy Geothermal Insulation System

3.1 Overview and References
These papers describe the development, analysis and implementation strategy for a system that utilizes ground heat as an active insulation layer that reduces the heat loss through a building façade.

Papers:

In submission
Forrest Meggers, Luca Baldini and Hansjürg Leibundgut. An innovative use of renewable ground heat in a building insulation system. In submission 2012.

CISBAT
3.2 Context of Papers

The viewpoint that led to the consideration of wastewater heat recovery in terms of exergy later incited the development of another even more novel concept. This concept is the active low exergy geothermal insulation system, which exploits the constant temperature in the ground, which is warmer than outside winter conditions, to increase the temperature of the building shell through a thin layer of piping in the façade. The first paper presented on this system provides the analysis and proof of concept through a dynamic model. It has been submitted to the journal *Renewable Energy* under the title “An Innovative Use of Renewable Ground Heat in a Building Insulation System.”

This concept played an important role in the design of the low exergy building being built by Professor Leibundgut at Bolleystrasse 35 (B35). Initially the wall concept was part of the building plan and energy system, and had to be part of the requisite energy analysis. In the end another novel wall construction was chosen, but the energy analysis led to the development of a second paper presented at CISBAT 2009 International Scientific Conference – Renewables in a Changing Climate from Nano to Urban Scale. This paper is titled “Active Low Exergy Geothermal Insulation System,” and is led to the acronym ALEGIS for the system. In this paper we evaluated the potential influence of such a system on the annual heat demand and thus its relative performance compared to typical insulation standards. This allowed for an interesting discussion about how building regulations or prescriptive energy evaluations sometimes create barriers to new design concepts, and how adaptation in the analysis may be necessary. In this case the analysis allowed for an analogous result to was is typical used in passive insulation systems and it was accepted by the building authorities.

One of the reasons that the system was eventually not implemented in the B35 building is that the added benefit to a new construction is not substantial compared to the installation cost. The development of this system actually supports better the renovation of buildings using low exergy systems. It is often difficult to reduce the heat demand of buildings to a low enough level to allow for low temperature heating supply structures, which require large surface areas. This difficulty in heat demand reduction is often the result of limitations to how much thickness can be added to a façade. This system provides a very lean construction that can reduce the heat demand very effectively, and most importantly for this case, reduces the peak design demand dramatically. The building wall stays relatively constant while the outside temperature changes, including during the coldest periods when the heating supply system would otherwise have to supply the largest amount of heating power. Therefore this system is very well suited to allowing low exergy renovations by facilitating the installation of low temperature heating systems, and on top of that it provides a second usage for the installed geothermal borehole.

This research resulted in the creation of a novel insulation system that uses heat from the ground in the wall. The operation of the system minimizes the destruction of exergy by heat transfer through the wall into the environment, but this representation is achieved by recognizing the ground heat as a free heat source. It is this type of thinking that brought about the use of the terms exergy and anergy as representation for energy supply to the building (exergy) and energy exploitation from free sources (anergy). In this example, the wall system uses the dispersed energy in the ground that is at equilibrium (a defined state of anergy) as a heat source, which then helps minimize the electricity input in to a heat pump system (electricity is 100% exergy) to supply heat.
Paper 3.1: An innovative use of renewable ground heat for insulation in low exergy building systems
Forrest Meggers, Luca Baldini, Hansjürg Leibundgut
In submission 2012

Keywords: buildings; insulation; geothermal; ground heat; heat pumps; energy efficiency

Abstract
Ground heat is a renewable resource that is readily available for buildings in cool climates, but its relatively low temperature requires the use of a heat pump to extract it for heating. We developed a system that uses low temperature ground heat directly in a building wall to reduce transmission heat losses. The Active Low Exergy Geothermal Insulation Systems (ALEGIS) minimizes exergy demand and maximizes the use of renewable geothermal heat from the ground. A fluid is pumped into a small pipe network in an external layer of a wall construction that is linked to a ground heat source. This decouples the building from the outside temperature, therefore eliminating large peak demands and reducing the primary energy demand. Our steady-state analysis shows that at a design temperature of -10 °C the 7 cm thick active insulation system has equivalent performance to 15 cm of passive insulation. Our comparison of heating performance of a building with our active insulation system versus a building with static insulation of the same thickness shows a 20% reduction in annual electricity demand, and thus exergy input. We present an overview of the operation and analysis of our low exergy concept and its modeled performance.
Introduction

We have developed a building insulation concept that utilizes renewable geothermal energy to actively reduce the dispersion of exergy from the conditioned space to the environment. We have named it ALEGIS (active low exergy geothermal insulation system). The new concept improves building performance by using the temperature of the ground in a small layer of the building facade. Small pipes are embedded in a thin outer layer of the facade. The layer consists of the simple piping structure attached with thermally conductive cement and covered in a thin thermally resistive plaster. A geothermal heat exchanger and a small circulation pump provide fluid at ground temperature such that the wall has a constant temperature. This eliminates the effects of lower outside temperatures, reduces building heat loss, and it utilizes the heat of the ground directly. Still, a heat pump or heating system has to be used to provide the base heat demand. In this case the heat demand is reduced and at a constant level, which allows the heat pump to be optimized for nearly constant conditions.

During cold outside conditions the same reduction in heat transfer through the facade is achieved by ALEGIS as would be achieved by much thicker passive insulation. The combination of high performance and a thin installation makes the system ideal for renovation. This is ideal for projects where a heat pump could provide the optimal performance, but the heat loss from the building is too high to be effectively provided by a heat pump. Also this provides a second function for the ground source heat exchanger, which can be expensive to install. It provides the facade with the ALEGIS heat barrier, as well as an ideal source for a heat pump.

Background

The impetus for this seemingly strange idea of supplying heat to the outside of a building came from the combination of research into low exergy systems [1-6], combined with a desire for high performance facades without excessive thickness. Based on the awareness of the disadvantages of very thick passive house walls [7], along with the need for thin renovation options, the ALEGIS concept was developed. If one actively heats the outer side of the wall construction, a virtual translation of the wall into a warmer climate zone is achieved. The building feels as if it is an earth-sheltered structure, which have been shown to have great performance benefits [8]. Not only that, but this active system has the ability to be turned off, which makes it adaptable to the potential problem that heavily insulated building have of overheating. This allows the system to selectively eliminate large thermal gradients from extreme cold while remaining adaptive to warmer conditions.

The higher temperatures attainable from ground source heat exchangers in winter compared to the environmental temperatures, provides a large potential. It improves the performance of heat pumps measured by their coefficient of performance (COP), which is the ratio of heat supplied to work input. With ALEGIS, we have gone one step further and found a way to utilize this higher temperature directly in the building structure to reduce heat demand.

The concept is possible because the ground temperature remains constant below a depth of around 5m [9]. The volume of earth creates an infinite heat sink or heat source limited only by the rate at which heat can be deposited or extracted [10]. In areas of high geological activity, high temperature sources can be found beneath the surface, but in most temperate locations the temperature is between 8 and 16 °C, and usually increases about 2-3 degrees with each 100 m of depth [9]. In layers closer to the surface, a strongly damped oscillation is
observed due to the changing ambient outside conditions. We have based our analysis on these typical conditions and the winter design conditions of Zurich, Switzerland.

Related Work

A review of literature and current technology exposes many innovative insulation concepts. One system that exploits heat fluxes in the façade is pore ventilation or dynamic insulation. These systems have been studied and implemented [11-14], but are generally integrated into new construction and require special ventilation control. An installation similar to ALEGIS that instead uses hot water for insulation purposes can be found in a building of the management school Zollverein in Essen, Germany. There, a water bearing system is directly integrated in very thin concrete walls, but this concept could only be realized because of the freely available 28 °C hot water originating from an old and unused coal mine [15]. Another similar concept has been described by Platell [16], where seasonal exergy is stored in the ground and subsequently used inside the walls of a building to provide heating and cooling. Also, a patent has been published about a wall construction that is actively insulated using a low temperature heat source [17]. It is equivalent to the concept presented in this paper, although it does not consider the exergetic benefits of such a system when integrated with a heat pump and does not give detailed design guidelines or any performance data. Finally, a research project of a similar system has also shown the importance of considering exergy in its development [18].

Methods

Wall Parameters and Dimensioning

For the analysis of the temperature distribution in an actively insulated wall, the following parameter values are assumed: The solid wall being a brick construction has a thickness of 0.18 m and a thermal conductivity of 0.44 W/mK. The plaster used to hold the tubes for the active insulation system has the same thickness as the diameter of the tubes, i.e. 0.01 m, and it has a high thermal conductivity of 0.7 W/mK to encourage uniform temperature distribution in the piping layer. Any insulation material used in the model is assumed to have a thermal conductivity of 0.07 W/mK. For analyses not dealing with insulation thickness, a default thickness of outer insulation that covers the piping of 4 cm is chosen. The working fluid has an average temperature of 285 K and a 2 K temperature drop is fixed across the wall system. By default a tube spacing of 5 cm is assumed which corresponds to 20 pipes passing within 1 m height of the wall. Room temperatures are fixed at 293 K where the default outside temperature is at 263 K. For the calculation of the convective heat fluxes the convection coefficient for inside is assumed at 8 W/m²K and for outside is assumed at 25 W/m²K. Radiant losses, even at the higher wall temperature, would be negligible compared to convective losses. The potential gains due to solar irradiation are ignored for this analysis to maintain a neutral case for comparison.

Wall Temperature Distribution and Tube Spacing

The heat fluxes in the different layers of the wall construction must be evaluated in order to compare typical static insulation to this active concept. It is important to determine the interface temperature in the wall where extra heat from ALEGIS is supplied. This temperature depends on the small amounts of insulation installed above and below the piping system as well as the piping spacing. The temperature in this layer will vary between the piping, which will influence the performance of the system and will determine the optimal insulation and tube spacing of the system.
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A simple model estimates the temperature profile in the piping layer of the wall. Assuming one-dimensional heat transfer through the wall and regular tube spacing, an average temperature was calculated for the piping layer based on the heat flux through the wall-area containing a tube and the wall-area between tubes given in Equation (1). For cold outside conditions the actual maximum temperature in the piping layer would be found at the pipe, and the minimum would be found at the midpoint between two pipes. Assuming that the vertical temperature gradient at these two points would be zero, a simple third-order polynomial was determined to estimate the profile and the minimum temperature between the pipes. The polynomial coefficients were found by setting the integral over the one wall section equal to the average temperature from Equation (1).

\[
T_{ave} = \frac{U_{out} * T_{out} + U_{in} * T_{in} + 2(A_{pipe}/A_{between}) * U_{piping} * T_{pipe}}{U_{out} + U_{in} + 2(A_{pipe}/A_{between}) * U_{piping}}
\]

Comparison to Static Insulation

The thermal resistance of static insulation on the outside of a wall raises the temperature underneath the insulation compared to cold outside conditions, but this temperature also varies with the variable outside temperature. The active insulation system fixes the temperature under the insulation so that the outside temperature has minimal effect on the wall. We compare the average temperature under the active insulation to the amount of static insulation required to achieve that temperature at various outside temperatures. The colder the outside temperature, the more static insulation would be required to match the performance of the active system.

The equivalent static insulation is calculated by first determining the heat flux in the active system between the inside temperature and the average piping layer temperature. This heat flux is then used with the actual outside temperatures to calculate an equivalent thermal resistance, \( R_{eq} \), of the active system, Equation (2). This equivalent thermal resistance can then be used with a standard insulation material to determine the thickness required to achieve the same performance, Equation (3).

\[
(2) \quad R_{eq} = \frac{1/U_{in} * (T_{in} - T_{out})}{(T_{in} - T_{ave})} - \frac{1}{h_{in} + dx_{wall}/\lambda_{wall} + 1/h_{out}}
\]

\[
(3) \quad dx_{eq} = R_{eq} * \lambda_{eq}
\]

System Performance Comparison

The flow of heat from the ground into the piping layer of the wall requires pumping energy. Instead increasing the temperature of this heat using a heat pump so that the building can be directly heated, part of the ground heat is used directly in the wall to reduce the heat demand of the building. This allows a comparison of a typical heat pump COP, and the overall COP of this active system. The active system COP can be considered in two ways.

First, a simple pump COP can be described as the amount of heat that is supplied to the wall directly relative to the pumping work input. Second, a virtual heating COP can be defined as the amount of heat loss that is avoided or blocked by the piping layer in the wall relative to the pumping work input to achieve this effect. The second ratio presents the most realistic comparison to the heat pump COP because it relates directly to the heat demand of the building. This comparison is illustrated in Figure 3.1.
Figure 3.1: Heat pump versus circulation pump + heat pump. In (a) a typical heat pump energy flow is illustrated where heat is brought up from the ground, $Q_g$, at ground temperature, $T_g$, and a heat pump, HP, uses exergy or electricity, Ex to increase the temperature of that heat for heating to $T_h$ to meet the heat demand created by the insulation, $Q_h$. In (b) the ground heat is used partially for the heat pump, HP, and part in a simple circulation pump, CP, so that the wall temperature is reduced to ground temperature and the building heat demand is reduced by the active insulation.

In order to make such a COP comparison the actual pumping costs must be estimated, and these depend on the building size and outside temperature. Therefore a very generic building model is employed along with weather data for Zurich, Switzerland [19].

A cubic building was assumed with 10 m by 10 m walls and roof. It was assumed that the shell of the cubical building was constructed of with the same 18 cm block wall construction as described above. This combined with a horizontal cross flow topology, pipe spacing, and pipe diameters allowed for a calculation of the pressure drop of the system. It also allowed an estimation of the necessary ground source heat exchanger size and depth. The pumping costs of the geothermal connection for each wall could then also be considered.

The total annual heating demand of the building was evaluated for the different insulation methods. The final demand of an integrated heat pump system was also compared. This includes the analysis of the active wall performance with the ground source heat exchanger loading and its extra pumping requirement, as well as the pumping demand for the wall itself.

The annual temperatures during winter, taken from weather data for Zurich, Switzerland, produced an hourly heating demand for the sample 10x10x10m building. The system performance was calculated using three scenarios for the building insulation. These were the active insulation system, the static insulation of equivalent thickness, and finally the un-insulated brick wall, which provided a basis for potential benefit in renovations to older constructions.

**Pressure Losses**

The total system pressure loss of the active insulation system and the ground source loop must be evaluated in order to estimate the pumping costs. The mass flow is only dependent on the system heat loss because the temperature drop across the wall is fixed at 2 K.
Therefore the pressure losses are also dependent on only the piping layer heat loss, and thus the outside temperature.

For the calculation of the pressure loss, both major and minor losses were considered. The major pressure loss in the wall is calculated based on the number of tubes, their diameter and their length for each wall section of the building using standard fluid dynamics methods [20]. The minor losses occur in the fittings that connect the parallel branches to the major branches. For each horizontal branch a loss factor of 1 is assumed at each T-junction along with a factor of 0.08 and 0.13 for contraction and expansion respectively. The pressure loss from the larger main vertical supply branch is small and neglected. For the ground heat exchanger loop, a single U-tube heat exchanger is used for the analysis and the pressure drop is based on the major losses from twice the length of the borehole. The total mass flow is equal to the number of horizontal branches times the mass flow per branch determined by the heat demand.

The total pressure drop in the system is calculated assuming one 300m deep bore hole with a single U-tube of 0.05 m diameter connected to the active insulation system with the piping network on each 10m x 10m surface. The total efficiency of the circulation pump was taken to be 25% in accordance with commercially available models.

The electrical work input for a circulation pump is calculated based on the operating conditions expressed by the total pressure rise and the flow rate, and the total pump efficiency shown in Equation (4).

\[
Ex_{\text{pump}} = \frac{\Delta p \cdot V}{\eta}
\]

With the determined pump work, the equivalent COP of the system can be calculated. The heat demand reduction achieved can be used to create a ratio with the work input of the circulation pump. This was used in the comparison to heat pump performance in standard installations.

**Ground Source Heat Exchanger**

The performance of the ground source heat exchanger was checked to confirm the assumed temperatures and flow rates coming into the active insulation system. This was not directly integrated into the model. The calculations are based on the work of Claesson and Eskilson in Sweden [21] using the Earth Energy Storage (EED) software. The loadings for the 10x10 m surfaces of the cubic building were compared with EED to check for adequate borehole length and verify the assumed temperature input coming out of the ground heat exchanger system. These dimensions allowed the pressure drop and pumping costs for the entire system including wall and borehole to be analyzed. Because both systems assumed the use of a heat pump with the same ground source, the pumping costs of the boreholes for the heat pumps themselves would be similar and can be neglected in the performance comparison.

**Active Insulation Heat Pump Performance Enhancement**

The effect of the active insulation is not limited to an improvement of just the walls. The entire building system can be improved when an active insulation is integrated. This is the case when the cyclic performance of a heat pump is considered. Under normal operation a heat pump has to cycle on and off or operate with a variable speed drive in order to satisfy the heat demand that changes with changing outside conditions. This causes the heat pump to operate below its optimal efficiency. These losses were quantified in our model based on data for the cyclic degradation of heat pumps [22]. It was found in Switzerland [23]
that heat pump performance is generally reduced by about 20 percent due to realistic loading scenarios. Also the standards for heat pump ratings in the United States assume a cyclic degradation coefficient of 0.25 which corresponds to losses of about 12 percent due to cyclic loading of heat pumps [24]. The active insulation system will provide a relatively constant heating load to the heat pump system as shall be shown later. Therefore these numbers were input into the model to estimate the performance difference of a heat pump operating under variable conditions versus one operating with a constant buffer from active insulation.

**Results**

**Wall Temperature Distribution**

The resulting temperature distribution in the piping layer is shown in Figure 3.2. The average temperature is shown as a horizontal line, and the approximated temperature distribution curve is plotted. The maximum temperatures at the edges represent the tube location and the minimum in the center represents the coolest part between tubes. The case plotted is for 5 cm tube spacing and 263 K outside temperature. In this case, the maximum temperature deviation between the water temperature and the temperature in the middle between two tubes is 1.75 K. The average temperature level between the tubes is 284.1 K, which is slightly less than 1 degree below the water temperature. If the piping layer temperature differs too much from the water temperature, the effect of the water insulation is insufficient and the spacing between the tubes has to be reduced or the outer insulation on top of the tubes has to be increased.

![Figure 3.2: Temperature profile for the conducting plaster layer between the tubes for 5 cm tube spacing, 263 K outside temperature, and 293 K inside temperature giving 284.1 K average plaster temperature.](image)

The pipe spacing and the amount of insulation placed on top of the piping layer determine the temperature profile, and thus the average interface temperature of the piping system and its overall performance. Therefore, the spacing and thickness were explored to determine an optimal performance that maintains a thin profile without excessive insulation, while also not requiring an excessive amount of piping to be installed. The pipe spacing was evaluated in Figure 3.3 and the outer insulation in Figure 3.4 at a design condition of 263 K.
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Figure 3.3: Variation of plaster temperature with different outside temperatures and different tube spacing (dx).

Figure 3.4: Change in the temperature profile between pipes in the heated wall layer with varying outer insulation thickness (dx).

Equivalent Static Insulation Comparison

The active system provides insulation against a cold outside temperatures, and the performance has been equated to the thickness of static insulation that would be required to achieve the same heat transmission reduction. This performance, measured by this equivalent insulation value, increases for the active system as the outside temperature decreases.

Besides being dependent on the outside temperature, the performance can be influenced by both the insulation behind and on top of the active water layer, as well as the temperature of the water supply. The water supply temperature is fixed by the geothermal conditions and depth of the borehole, but the insulation levels serve as design parameters that have been explored. When no or very little insulation is added on top, cold conditions make it is impossible to reach a homogeneous temperature in the water layer. The insulation behind the piping is necessary to create an acceptable heat flux between the inside and the active water layer, essentially the proper insulation for an outside temperature equal to the temperature supplied by the ground heat exchanger.
Figure 3.5: Variation in the equivalent static insulation thickness as a measure of the active system performance for different amounts of outer insulation for the system.

The change in the equivalent static insulation value for the active system with varying amounts of outer insulation and at different outside temperatures is shown in Figure 3.5. It is clear that the first few centimeters are very important in achieving a reasonable performance, but the impact is greatly reduced as further amounts are added. Beyond 3 or 4 cm of outside insulation the increase in equivalent static insulation is less than the actual amount of outer insulation added.

Figure 3.6: Variation in the equivalent static insulation thickness as a measure of the active system performance for different amounts of inner insulation installed behind the piping layer. Here the slope or ratio of increase in equivalent insulation and inner insulation is constant and more importantly greater than one.

Adding internal insulation behind the piping layer causes an expected linear increase in performance as shown in Figure 3.6, and more interestingly for each cm of internal insulation added, the amount of equivalent static insulation increases by a larger factor. This ratio is caused by the fact that the temperature difference across the inner insulation added to the system is between the room temperature and the active layer temperature, whereas the value of equivalent static insulation is determined across the difference between the outside temperature and the room temperature. Therefore the ratio of these temperature differences causes the inner insulation to have a greater impact per
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centimeter. Adding just 3 cm of internal insulation increases the equivalent insulation thickness from 8.4 cm to 18.1 cm.

The internal insulation also provides a base performance level when the active system is not running. It can be seen in Figure 3.5 and Figure 3.6 that at the warmer outside temperature of 278 K, the equivalent static insulation value is near the actual system thickness, making the active operation redundant. During mild conditions the system can be turned off and achieve reasonable static performance with the inner and outer insulation layers. In this way the system acts as a buffer that virtually eliminates the impact of the coldest temperatures on the heat demand of the building, while providing adequate insulation at mild temperatures.

**Heat Loss Comparison**

A direct comparison of the heat loss per unit area of wall is given in Figure 3.7. A symmetrical setup with 3 cm of outer and inner insulation was found to have a good performance for comparison to standard construction, and is still fairly thin. The active system is compared over a range of outside temperatures to the base construction with no insulation and to standard passive insulation 7 cm thick, equal to the active system total thickness.

The heat losses are smallest for the active insulation except for high outside temperatures where a regular static insulation of the same thickness performs better. The most remarkable property of the active insulation is apparent in the slopes of the curves. The active insulation produces a very flat, almost horizontal curve for the heat loss. This means that the heat loss becomes almost constant, independent of the outside temperature.

![Figure 3.7](image)

**Figure 3.7:** A comparison of the heat loss through a unit area of wall for the uninsulated base case and the equal-thickness passive and active insulations.

Not only is the performance of the active wall better, but also the operation of the entire building system is presumably more efficient. The heat demand that must be supplied to the building is maintained at a rather constant level. This has the potential to improve the performance of the heat pump system as well as the lifespan because turning systems on and off or modulating components leads to more rapid deterioration.
Full system annual performance

The annual performance is calculated for Zurich, Switzerland. We display the annual heat demand for the active insulation wall and for a static insulation wall in Figure 3.8, along with the mass flow demanded by the system. The static insulation has a thickness 7 cm, which is equal to the total thickness of the active system with 3 cm of inner insulation and 3 cm of outer insulation.

![Figure 3.8: Annual heating demand per unit wall area for the three construction types plotted with the mass flow rate for one 10x10m wall.](image)

Figure 3.8 shows that for the same insulation thickness both systems significantly improve the un-insulated wall, but the active insulation has the added benefit of providing a relatively constant demand as shown by the dark blue flat curve for the active insulation. The plot of the mass flow demonstrates how the mass flow of the system can be controlled to achieve the flat demand. This control is easier and more efficient to achieve with a simple pump than the varying climate control that would need to be supplied by the heat pump or other heating system. Also, one can imaging that in Figure 3.8 the heat losses with no insulation and with standard insulation would also increase more in colder climates, whereas the active system would only increase its pumping cost. Therefore the active system will increase its performance for colder climates as long as sufficient ground source heat is available.

Borehole Performance Check

The performance of the ground source heat exchanger (GSHX) was evaluated using the EED software for depths from 100 to 300m with heat demands for single walls and for the entire structure. The borehole performance was shown to be sufficient as long as there was some recovery loading during the summer, which would be expected from the heating up of the wall during the warm months as well as from solar irradiation. There is some temperature variation over the winter months that could bring the temperature down to 8 degrees C. The loading selected for the analysis was for the use of one 300m deep borehole for the theoretical 10x10x10m building. An average subsurface temperature of 8 degrees was assumed for Zurich with a positive gradient of 3 degrees for every 100m of depth. Based on the EED analysis including summer regeneration and with this depth and temperature gradient, a temperature of 12 °C could be assumed for the wall.
**Annual Demand**

The total annual electrical energy demand to run the heat pump for the static and the active systems is shown in Figure 3.9 and Figure 3.10. The blue sections show the electricity supplied to the heat pump to meet the heat demand plotted in Figure 3.8 for each system. For the active insulation (bar 2), the light green section shows the pumping demand through the wall piping ('ww') and the red section shows the pumping demand through the ground heat exchanger ('GHE').

![Figure 3.9: Static insulation of 7 cm versus active insulation of 3x1x3 cm comparison including extra pumping demands where 'HP' is the exergy supplied to the heat pump, 'ww' is the exergy supplied to the circulation pump and 'GHE' is the exergy supplied to the wall's ground heat exchanger circulation pumps.](image1)

![Figure 3.10: Static insulation of 5 cm versus active insulation of 2x1x2 cm comparison including extra pumping demands where 'HP' is the exergy supplied to the heat pump, 'ww' is the exergy supplied to the circulation pump for the water in the wall and 'GHE' is the exergy supplied to the wall's ground heat exchanger circulation pumps.](image2)

This is again for a 10x10x10m building, and includes an integrated heat pump system with the COP adjusted in the static case due to cyclic loading as described in the methods. In Figure 3.9 the active system (bar 2) shows an advantage compared to the static case (bar 1) of about 20% for the case of a 7cm overall wall insulation thickness (4700 vs 5700 kWh/a). When the overall thickness is reduced to 5cm, Figure 3.10, the advantage is slightly lower at
about 15% (6100 vs 7000 kWh/a) because the pumping demand in the active system for the ground heat exchanger increases from 200 to 650 kWh/a and for the wall from 50 to 120 kWh/a. In any cases there is a dramatic improvement over the wall with no insulation, which would have an annual demand of three times higher at 16,000 kWh.

Because the active water wall system provided a rather constant heat demand for the building as shown in Figure 3.8, it was interesting to look at the annual performance using an integrated heat pump. The weather data for Zurich proved that the active system could indeed outperform a standard system. Nevertheless, the performance increase of 15-20 percent might not easily payback the additional costs of the system. But still, if a borehole is going to be installed for a heat pump system anyway, this system will utilize of components most effectively. The constant heat demand has potential to improve not just the performance of the system, but also the lifespan because turning the systems on and off or modulating components would lead to more rapid deterioration as well as more complicated control. In this system a simple temperature sensor for flow control is needed for the active insulation circulation pump.

The effect of different fluid temperatures in the active wall was also observed as shown in Figure 3.11. As expected, the annual demand is decreased as the temperature is increased, but also as the temperature is increased the pumping demand increases because the temperature creates a higher heat flux out of the pipe layer into the environment, which increases the pumping demand. This results in a rather constant total system demand with varying temperature as shown in Figure 3.11. The higher pumping demand caused by the large flow rate per borehole could be reduced by adding more boreholes, and would be necessary to maintain reasonable borehole heat demand.

![Figure 3.11: Total annual demand in kWh versus different water temperatures in the wall showing the change in heat pump demand 'HP' and pumping costs from the wall 'ww' and ground loop 'GHE'.](image)

Based on a traditional view of the COP of a heat pump, the ratio of annual heat moved to annual electrical input can be evaluated for the circulation pump. For conditions in Zurich, a simple pump COP would be 23. This means that for every 1 unit of electricity going into the pump, 23 units of heat are provided to the wall. This is made possible because the heat is freely available from the ground and does not require any thermodynamic transformation. Nevertheless, this heat does not go to heating the building, but rather to increasing the
building surface temperature, which subsequently decreases the building heating demand and increases the heat pump performance.

Using this reduced annual heat demand, the virtual COP for the circulation pump is evaluated. Here it is the difference between the annual heat demand with the system on versus the demand with the circulation system off. In this case the COP is 15. Therefore for every 1 unit of electricity annually supplied to the pump, 15 units of annual heat demand are eliminated. Both for this virtual COP of 15 and for the absolute COP of 23 described above, the value is much higher than any real heat pump today. This justifies the additional use of this pumping system along with the standard heat pump installation. Although this active system incorporates a wider range of components and complexity, it has the potential to provide very high performance, especially when thinner walls are desired or necessary.

**Costs and Payback**

The costs as compared to a standard system have not been precisely evaluated. The additional cost will come primarily from the purchase and mounting of the piping system to the wall. This could be minimized by simplifying and mass-producing the technology. The pipes could easily be draped from a large supply pipe and plastered over without much additional labor cost, and small plastic tubing can be obtained for reasonable prices. Still, simple spray-on insulation will always be less expensive, but it has limited application thickness and thus limited performance. When the performance of the active water system exceeds these limits, then the system becomes market viable because thicker more extensive insulation installations beyond spray-on plaster result in much thicker walls. They will have a comparative cost to that of the active water system. In these cases when a heat pump is installed as well, the active water wall system will be very competitive.

**Conclusion**

We have presented an analysis of the ALEGIS concept that demonstrates the feasibility of such a construction. A potential construction has been reviewed, and the performance has been compared to a similar retrofit using standard insulation.

The initial analysis of the temperature distribution between the pipes showed that a reasonable temperature distribution and average temperature could be achieved with 1 cm pipes spaced every 5 cm. For this performance the number of pipes was not insignificant, but the installation is still feasible. The amount of outer insulation needed for a good average temperature was approximately 3 centimeters.

We explored of the effects of the amounts of insulation installed below and on top of the active water layer, and compared that to the performance of static insulation. Here the results were mixed because at mild temperatures the active system, while much more complex, did not drastically outperform static insulation. On the other hand, during cold temperatures the system was capable of achieving excellent performance as compared to static insulation. For example, with just 2 cm of inner insulation and 4 cm of outer insulation, the 7cm thick system is equivalent to 15 cm of standard insulation at 263 K. This is more than double the system thickness. We also calculated the heat loss of the active system compared to a static system of the same thickness, which showed the superior performance at cold temperatures and showed that the active system could be beneficial up to temperatures around 278 K. The active system also maintains a relatively constant heat flux over varying outside temperatures, which provides added benefit to the operation of building heating systems.
The annual performance of the system was modeled for outside temperatures for Zurich, Switzerland. The overall system performance is compared to a standard heat pump installation. The annual electricity demand is about 5000 kWh for the active system including pumping costs while a system with an equivalent amount of passive insulation (7cm) is 20% greater at 6000 kWh. The annual electricity demand for this system is minimized with around 3cm of inner and outer insulation around the piping layer. This minimizes pumping costs while maximizing heat pump performance and lifespan by buffering the varying heat load from changing winter conditions.

Although many aspects of this potentially innovative new building facade system have been analyzed, there are still many questions left. Further analysis and optimization may prove that for highly integrated building renovation and system retrofits, it may be the best option. For extensive renovation this may provide the extra performance needed to bring buildings into the realm of zero-CO2 emission performance. It provides a very novel concept for reducing heat loss from a building that provides a thinner alternative to simple standard thermally resistant insulation. We have proven it to be an interesting concept worthy of investigation, and initial prototypes are under construction. We hope that it can provide an additional tool to facilitate the reduction of primary energy demand in the building sector, especially by expanding the possibilities for performance increases through renovation and retrofit to the existing building stock.

References
An innovative use of renewable ground heat in a building insulation system


Paper 3.2: Active LowEx Geothermal Wall Insulation System

Forrest Meggers, Luca Baldini, and Hansjürg Leibundgut


Abstract

We have designed a new building wall that utilizes the low value energy from a ground source heat exchanger (GSHE) to increase the external temperature of the wall above cold outside temperatures during the heating season. This makes the buildings feel as if it has been moved to a warmer climate, or alternatively seem as if it is has been buried underground where there is a constant moderate temperature. This drastically reduces the heat loss from inside the building as the temperature of the wall is constantly between 8 and 14 degrees Celsius all winter depending on depth and operation of the GSHE.

We present the first realization of this concept in a wall being designed for the B35 low exergy (LowEx) building project in Zurich, Switzerland. With a relatively thin construction of only 38cm, we show how the wall can meet passive house standards. But this is just for the coldest month of January, because the active insulation performance varies over the year according to the outside temperature. A successful calculation of a wall U-value for use in the Swiss energy norm is also demonstrated. In the end, a very high performance wall has been designed that is not excessively thick. In essence the system allows for an additional 10 m² of living space on each floor of the building compared to what would be available with typically thicker passive house walls.

The active wall is part of a fully integrated low exergy (LowEx) system. The heat pump performance in an integrated system can be maximized because the heating demand for the heat pump is held constant by the wall, thus eliminating losses due to cycling on and off, or due to variable speed drive inverters.

These concepts are all parts of the group of LowEx systems that are being demonstrated in the B35 building (www.viagialla.ch). The high performance thin wall is realized using high performance foaming concrete with a layer of EPS foam and an outer layer of insulating plaster. The integration of a new special GSHE and heat pump with heat recovery are also being designed and planning is nearly complete with construction beginning in 2009.

Introduction

High performance buildings place strict requirements on the walls of a building, to reduce the amount of heat loss. Buildings that meet the passive house standard can often be recognized not just from their energy performance, but already at first sight because of the thick well-insulated walls. Unfortunately thick walls are not always aesthetically pleasing and they also consume valuable interior space.

This new concept for wall insulation was a result of the desire to reduce the thickness of walls needed to meet the demands of high performance buildings, while also providing a thinner installation option for retrofits. Instead of increasing the resistance to heat flow through the wall using static insulation, we recognized the inherent value in ground heat and used that to decrease the temperature gradient across the wall. Research into ground
heat extraction especially for integration into heat pump systems has been studied for many years [1, 2, 3]. Research has shown that with proper sizing of a ground source heat exchanger based on heat demand, a relatively constant temperature can be extracted throughout the winter [4]. Still, typical ground temperatures are at least 10°C cooler than comfortable temperatures demanded for buildings with Zurich having temperatures of about 8°C and increasing about 3°C for every 100 m of depth [5]. Therefore ground heat cannot be used directly inside the building.

Through our research in the field of exergy and buildings [6], which considers the second law of thermodynamics, we were interested in maximizing the performance of heat pumps. This performance (COP) is the ratio of heat supplied Q to electric work input, W, and it is limited by the temperature difference that the heat pump must overcome as shown in Equation 1, where \( T_h \) is the heating temperature, \( T_g \) is the supply temperature and the \( \eta_{\text{Carnot}} \) describes the internal losses of the system and is usually around 0.45 to 0.50 for a good heat pump.

\[
COP = \frac{Q_{\text{supply}}}{W_{\text{electric}}} = \eta_{\text{Carnot}} \frac{T_h}{T_h - T_g}
\]

The lower the temperature difference is, the higher the COP becomes and therefore the more heat you get per unit electricity. In this case, the heat from the ground is freely available low quality energy that could be considered dispersed energy or ‘anergy’ as described in previous work [7]. The performance of the heat pump is only dependent on the temperature of the ground heat and not on its quantity. Unfortunately the temperature is fixed by ground conditions, but by viewing this anergy as freely available we are able to consider an application that might demand a large quantity. Figure 3.12 describes how heat from the ground can be used directly at its lower temperature in an external layer of the façade to reduce the temperature gradient and thus transmission losses of the building during winter.

This low exergy (LowEx) active insulation system reduces the heating load of the heat pump by cancelling out all outdoor temperatures that would be below the ground temperature. In other words, the building walls do not feel any extreme temperatures of winter. It is as if
they are buried in the ground, and the benefits of buried or earth-contact buildings has a long history and proven benefits [8].

It was initially unclear whether the idea would be feasible. There would be additional pumping costs and the temperature outside is not always lower than ground temperature over winter. An initial study was done looking at the potential design and performance of the system and its subsequent feasibility [9]. This found that a system of inexpensive 1cm pipes with 5 cm spacing between each other could provide an even temperature using ground heat at 12°C at the outer layer of the wall when covered with only 2 – 4 cm of insulating plaster. It was also shown that at the outside design temperature for Zurich of -8°C with just a 6-cm thick active wall layer attached to an 18cm concrete wall, a performance could be achieved that was equivalent to 20-cm of quality static insulation achieving an equivalent U-Value of 0.10 W/m²K that is below passive-house standards. The effect of varying the amount of insulation below and above the piping layer was analyzed as well as the topology of the piping installation. The required mass flow rate was considered to estimate the pressure losses and pumping costs, which were less than 1% of the heat energy lost per m² of wall.

A second study was done in parallel looking at the integration and influence of the active insulation system [10]. This compared two 10x10x10 meter buildings. One had a ground source heat pump and integrated active insulation, and the other had the same heat pump, but in this case an amount of static insulation equal to the total active insulation thickness was used. The active insulation also included the pumping costs for the wall as well as the extra pumping required for the larger amount of heat from the ground source heat exchanger. What is more interesting is that the cyclic on-off losses of the heat pump due to varying outside temperature could be eliminated. The end result was that the active insulation system, when designed with a total thickness of 5-cm or 7-cm had about a 15 and 20% better performance for the winter season in Zurich. Even though the performance at low temperatures is many times higher than the static insulation [9], the frequency of higher-than-design-temperature periods marginalized the improvement somewhat. It is expected that the system would perform even better in consistently colder climates with good ground heat accessibility.

In this analysis we look at the application of this wall system in its pilot installation for the B35 building in Zurich. The goal was to analyze the wall performance so that it could be input into the SIA 380/1 energy verification by the building engineering firm.

**Method**

The SIA 380/1 requires the surface area of the building and the U-value of those external surfaces to determine the energy requirements. The virtual U-value for the active insulation system has already been evaluated for simple constructions [9], but in this case a realistic analysis of the actual construction shown in Figure 3.13 was needed.
The wall incorporates an expanded concrete with low thermal conductivity and a core of EPS foam is installed in the center. The active insulation piping is attached to the outside with a covering of insulating plaster for a total thickness of only 38 cm.

The same model from the previous analyses [9,10] was used with this wall construction to analyze the system. As shown in the previous models, the U-value changes for different outside temperatures, so a realistic annual value had to be evaluated. First the static U-Value was calculated for the wall without any fluid flowing through it. Then the operation of the active insulation was analyzed over a range of temperatures, and the outside temperature where the benefit of the active system becomes negligible compared to the static wall.

The annual performance was determined by using hourly weather data from 1999, 2003, 2006 and 2007 for the temperatures of Zurich, and the average U-value for the wall for different temperatures and different times of year were calculated. An average U-value was calculated for the entire year, the winter half of the year, and for each month to give an idea of the variation in performance with the changing seasons.

**Results**

The wall performance over a range of outside temperatures is shown in Figure 3.14. The static U-value of the wall is about 0.25 W/m²K. The active system achieves better results than the static U-Value for outside temperatures below around 0°C. At the design temperature for Zurich of -8°C the system achieves the performance of a passive house.

For the annual operation of the wall the average annual U-values for each year are give in Table 3.1. The annual averages are close to the Minergie standard of 0.2 W/m²K and for the winter season the values meet the Minergie standard in most cases.

The average monthly U-Value for 2006 are shown in Figure 3.15. The variation between the results for different years was not significant enough to present. In this case the static value of just below 0.25 W/m²K during the months where the wall is not active, to 0.15 W/m²K during the month of January. This means that for the month of January the wall performs like a passive house or Minergie-P wall. Most Minergie-P walls have to be on the order 60-cm so at 38-cm this wall achieves the same performance during the coldest season with only 2/3 the thickness.

This data was presented to the engineering firm and they decided to use the annual average of 0.21 W/m²K for their SIA 380/1 energy norm calculations of the B35 building. This was a
conservative selection, but it provides a certain factor of safety. The SIA 380/1 calculation resulted in 131 MJ/m² of heat loss per year, beneath the annual allowance of 155 MJ/m².

![Figure 3.14: B35 active insulation performance.](image)

**Table 3.1: Average U-Values**

<table>
<thead>
<tr>
<th>Weather Year</th>
<th>Year Ave</th>
<th>15.Oct-15.Apr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>0.215</td>
<td>0.201</td>
</tr>
<tr>
<td>2006</td>
<td>0.209</td>
<td>0.189</td>
</tr>
<tr>
<td>2003</td>
<td>0.209</td>
<td>0.190</td>
</tr>
<tr>
<td>2000</td>
<td>0.210</td>
<td>0.191</td>
</tr>
</tbody>
</table>

![Figure 3.15: Monthly average U-Value for the active insulation system](image)
Discussion

We have looked at how one might implement an active low exergy geothermal insulation system, and calculations were successfully made to allow for a standard energy analysis of the B35 building, but the value used was actually quite conservative. Still, it was enough to meet the energy standards.

What is more interesting is how to evaluate the performance of the wall relative to absolute U-value standards like those of Minergie and Minergie-P. Is it possible to have a wall with better performance during different parts of the year, and does this allow it to meet the standards? This has not yet been addressed, but presents the potential for a very interesting debate. These standard have the goal result of reducing heat loss mostly during the cold season, so the performance improvement in the winter is ideal. But if it can still be said to meet the standard should be discussed.

Figure 3.16: B35 building rendering with a sketch of the active insulation piping system shown over one wall.

There are other potentially beneficial aspects that have also not yet been analyzed. This includes the ability of the system to absorb solar radiation, and to use that to regenerate or even store higher temperature heat in the ground heat exchanger. The active walls of the B35 building are planned to be black as shown in Figure 5, which will increase the albedo and increase the feasibility of this storage possibility in the summer. The installation of the insulation system will also help reduce the possibility of overheating by controlling the wall thermal mass.

Other important future work includes determining an optimal working fluid. Preliminary work has shown that more viscous materials can quickly increase the pumping costs of the system. Still, freezing would be a very detrimental event as the system will be permanently installed so there will have to be good safeguards against this possibility.

The system should also be considered for retrofit scenarios, because buildings built up through the 1970’s often have poorly insulated block walls that would be ideal for the installation of this system. This would also facilitate the retrofit of low temperature (low exergy) heat pump installations that are only possible when transmission losses are reduced.

Future analysis will continue to test the feasibility of this system. The cost of the installation will also be considered after this first pilot project, and could be initially prohibitive.
Nevertheless, it is a unique and interesting concept that deserves further testing and analysis.

Acknowledgements
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References
4 Exergy Concept for Buildings

4.1 Overview and Reference

This paper was developed to discuss the motivation and adaption of the concepts of exergy and anergy in the building field, and how these concepts can be utilized and leveraged to guide better building system design and integration.

Paper:


Selected for *International Journal of Exergy* publication from ELCAS 2008 conference:
4.2 Context of Paper

The design of the active insulation system generated a confrontation with the strict definitions of exergy and anergy used in thermal plant and heat engine analysis. The operation of a building is actually quite different compared to the systems that the concepts of exergy and anergy were actually invented for. For this reason some more exploratory research into how these concepts can be utilized for building design and performance analysis was performed in a research paper presented at ELCAS 2009, titled, “The Reference Environment: Redefining Exergy and Anergy for Buildings.” It has been submitted to The International Journal of Exergy under the title “The Reference Environment: Utilizing Exergy and Anergy for Buildings,” because it was decided that we are not in fact redefining exergy and anergy, but rather explaining how the concepts can be effectively applied to the design of building systems.

The paper helps support the way that the terms exergy and anergy have been employed for teaching architecture students. The idea of exergy and its quantification of the value of high temperature systems helps show students how the performance of heat pumps depend on minimizing the use of high temperatures. This is combined with the concept of anergy as the source of heat coming into a heat pump, and that by finding an anergy source of higher temperature the heat pump performance can be further improved. In this way the architectural students have simple ways to utilize these concepts that result in the same performance increases that would be made by doing a technical analysis using exergy, all without having to undertake the full thermodynamic derivation of energy and entropy flows.

Besides making the concepts more accessible to a broader audience of building designers, the research for this paper also demonstrates further a basis for the common use of a reference environment for buildings as the outside conditions. This has been an obstacle for researchers analyzing building systems using exergy, because one must define a reference state, and again, historically exergy analysis was done using a fixed reference state because the thermal plant or heat engine operations being optimized were done at much higher temperatures. In the case of buildings, the temperatures of interest are much closer to ambient temperatures so the analysis becomes more sensitive to the selection of a reference state. It also makes comparing analysis difficult, but nevertheless, by using the outside conditions, the actual potential of the building system can be evaluated. In the case of building systems, the goal of exergy analysis is to minimize the losses in quality in each part of the chain of exergy consumption, and this is relevant to the local conditions, not a universal standard.

This paper provides a basis for more uniform application of the concept of exergy. It helps to differentiate how exergy can be utilized to improve building systems, as well as to guide the design of better systems. This is done by contrasting the original uses of exergy for thermal plants and heat engines with the supply of exergy to buildings. Finally, an expanded view of the concept of exergy allows it to be more easily applied to buildings and more easily understood by architects and designers. The thinking along these lines has led to the development of an even larger pool of low exergy systems, which provide access to a new high level of performance for active building systems.
Paper 4.1: The reference environment: Utilizing exergy and anergy for buildings

Forrest Meggers and Hanjürg Leibundgut

International Journal of Exergy (in press)

Abstract

The utilization of exergy and anergy concepts for low exergy building design extends the potential performance optimization. A major obstacle in the application of this concept is the lack of an accepted definition of the reference environment. The absence of this factor leads to ambiguity in analysis and hinders comparisons between studies. Choosing these state variables influences the amount of exergy contained in the building and its system, and with the low quality levels often dealt with in buildings, the influence can be significant. We propose a new way of looking at buildings and their external environment. It recognizes exergy as the utilizable potential that maintains comfort inside relative to outside ambient conditions. It considers environmental heat sources as a form of transiting exergy that is utilized internally to increase second law efficiencies, and then returned to the environment. These sources are not chosen to optimize energy inputs, but rather temperature inputs. They are optimized as anergy sources coming from a dispersed state, which are transited through the building system and deposited back in an anergy sink, which defines the reference environment. From this perspective it becomes clear that using the ambient environmental conditions to set the reference environment produces the most relevant results in exergetic analysis of whole buildings, while also validating the unencumbered use of ambient anergy sources such as the ground, water, air and the sun to increase exergetic performance.
Introduction

The application of exergy analysis to buildings has been challenged by the ambiguity of a definition for the reference environment. This leads to some confusion in the resulting analysis when comparisons in methodology are made. There have been many discussions within the low exergy (LowEx) building community [1] about whether a specific reference environment is needed, and if so what it should be. We present the argument that there should indeed be a standard accepted methodology. We argue that a broader utilization of the concept of exergy and anergy for buildings improves design, and for exergy analysis of buildings, the reference environment should be the ambient environmental conditions.

Why Exergy and Buildings in the first place

Before we can discuss the argument for a standard reference environment for buildings, we must first ask ourselves what the purpose of exergy analysis of buildings is in the first place. The qualitative benefits and rationale of low exergy buildings have been made clear by the work done in the IEA ECBCS Annex 37 and Annex 49 and the resulting guidebooks [2, 3].

Buildings using low temperature heating systems and high temperature cooling systems designed according to low exergy principles perform very well. They have been shown to increase both comfort and efficiency [4-6]. This has expanded the research and application of exergy analysis in building design and system analysis [7]. Exergy analysis defines the locations within a building where the most potential improvements are possible. Observing the chain of exergy destruction, for example in a building heating system, demonstrates not only where energy is being wasted, but also where the value is being lost [8, 9]. This can be done at the energy source [10], for a set of buildings [11], for a single building [12], or for individual component comparison [13] or analysis [14]. Exergy analysis encourages the use of more efficient active systems that might not be considered otherwise. We are interested in its application to entire building systems and how it can be utilized as a method for better building design.

New building technologies are being developed based on the concept of exergy [15, 16], and simple quantitative and qualitative evaluation of the integrated performance of low exergy building systems demonstrate the great potential for exergy to improve building systems design [17, 18]. Recent pilot projects have also began to prove the potential implementation [19, 20]. The quantitative validation of some of these improvements under steady-state conditions is possible with exergy analysis software tools [8, 21]. These tools along with the qualitative philosophy of low exergy design expand the perspective available to building designers, and this already makes the concept of exergy valuable for building design.

Nevertheless, we are still lacking a specific methodology that can be universally applied in exergy analyses of buildings, especially when outside climate variations are considered. A methodology needs to be developed that facilitates comparison between exergy analyses, and provides a clear guide to low exergy design. This will lead to better tools that can both guide designers as well as demonstrate how the use of low exergy systems produces the most desirable results.

Steady State versus Dynamic Analysis

Exergy analysis is often applied to buildings under steady-state conditions to analyze specific systems under specified design or operating conditions, and can also be implemented in a dynamic analysis of seasonal operation. Studies have been made that
contrast dynamic and static analyses [22, 23], and in both cases there is no well-defined consensus on the definition of a reference environment. Studies have observed a potentially significant impact of variations in this reference environment for exergy analysis of buildings [7] based on the sensitivity of exergy analysis to the reference environment selection [24, 25], and the level of chemical exergy due to humidity and evaporative conditions [26, 27].

Steady state analysis has one advantage in the definition of a reference environment because when the system is assumed to be at steady state, then clearly the ambient environmental conditions are also in steady state. Therefore, if a heating system is being analyzed, the outdoor conditions in winter can be used, and for cooling, summer conditions. Contrary to this, dynamic analysis takes place over a period of varying ambient conditions, which leads to varying parameters in the reference definition. This pertains to whether the reference environment is fixed, follows the ambient conditions dynamically, or if it is a composite of seasonal conditions.

The ambiguity of this parameter leads to an additional problem for dynamic analysis. Unlike steady state analysis, which can have two systems under the same conditions easily compared using exergy analysis, a dynamic analysis may provide different comparative results depending on how the reference environment is defined. Therefore the definition of a standard methodology for reference environment definition is even more imperative for dynamic exergy analysis of buildings.

In fact, a framework is needed for exergy analysis of buildings for either steady state or dynamic analysis, which provides a logical result while also facilitating comparative studies. This requires a consensus on how exergy is considered when applied to an entire building system. A framework for a common utilization of exergy for buildings can provide the basis to build this consensus.

**Methods**

**Exergy was designed for engines, not buildings**

Exergy was developed as a concept for thermal systems, almost all of which were forward operating systems utilizing heat to produce work [28, 29], as depicted in Figure 4.1(a). In these systems, the reference environment plays the role of the low temperature sink, $T_{\text{Cold}}$ in Figure 4.1, defining the maximum potential of the process to output work, $W_{\text{out}}$. In high temperature combustion systems, such as power plants and propulsion engines, the reference environment can be easily defined as something close to atmospheric conditions with a reference temperature of 273 K to 298 K and a pressure of ~100 kPa. Variations of these values will have little impact on the exergy analysis of the system as described by Rosen and Dincer’s sensitivity analysis of the reference environment [24]. This simplifies the definition of a reference environment for high temperature systems, but for low temperature systems like buildings, the reference temperature has been shown by Sakulpipatsin to have a larger influence [26]. It is the goal of minimizing temperature differences in buildings that in fact makes the definition of a reference environment so important.
The reference environment: Utilizing exergy and anergy for buildings

Figure 4.1: Comparison of the operation of a heat engine that was origin of the concept of exergy with the operation of a building. The Carnot heat engine (a) takes heat from a hot reservoir and generates work through the flow of heat into a cold reservoir. The building (b) may take heat from a hot source for heating or from a cold source for cooling and both of these processes can be augmented by a work input.

In the case of buildings, which are also thermal systems, instead of a forward operating system to produce work, $W_{out}$ in Figure 4.1(a), a system is setup that consumes work to maintain a heat flux, $Q_{hot}$ or $Q_{cold}$ in Figure 4.1(b). This flux is what maintains comfort inside a building. The amount of heat flux needed to provide the comfort depends first on the building and its construction, and second on the ambient conditions. Thus the demand varies for different climates and throughout the annual seasons. In the case of a heat engine in Figure 4.1(a), the heat flux, $Q_{hot}$, and supplied temperature, $T_{hot}$, of the heat source can be easily approximated from the type and amount of fuel input, while assuming a reference environment at fixed temperature, $T_{cold}$. This facilitates exergy analysis of the engine system. Contrary to engines, in buildings it is both the heat source and heat sink temperatures, $T_{hot}$ and $T_{cold}$, and not just the heat input that define the operating criteria of the system, and instead of maximizing work output, $W_{out}$, as with engines, the goal is to minimize the work input, $W_{in}$.

Instead of maximizing engine output, exergy analysis of buildings can be used to minimize input. In a thermal system like the heat engine in Figure 4.1(a), exergetic efficiency can be defined as some ratio of a useful output to the total potential of the input. In the case of buildings, the useful output is just comfort, which is defined by the necessary heat flux of the building to the environment needed to maintain comfortable indoor conditions. This can be provided by a variety of exergy inputs. The exergetic efficiency of creating this heat transfer process can be influenced by independent changes throughout the input and output processes. The goal of exergy analysis of buildings, as shown in Figure 4.1(b), is to facilitate the minimization of the work input, $W_{in}$, as well as the output losses from transmission, ventilation, etc. Thus there is a fundamental difference of buildings compared to heat engines, and therefore the utilization of the concept of exergy for building design is one that must have a slightly different perspective than the common one for heat engine or thermal plant analysis [29]. This will help to produce an appropriate and common methodology for the reference environment.

Low exergy buildings use heat pumps, not heat engines

The basis for this approach can be further illustrated by again considering the operation of a heat engine, and this time comparing it to the operation of a heat pump as shown in Figure 4.2. The heat pump represents a low exergy method of heat supply to a building (or removal for cooling), which can be optimized using exergy analysis, and the work in these systems is here recognized as exergy output and exergy input. We also label the anergy sink in the reference environment of the engine and an anergy source for the heat pump.
The operation of a heat engine versus the operation of a heat pump. The heat engine uses a high temperature heat source to optimize the amount of Work, or exergy output, and is connected to a fixed cold reference environment, or anergy sink, which plays a small role in the engine performance because the heat source is usually a large temperature. The heat pump extracts heat from a source using the same engine cycle in reverse to supply heat at a higher temperature where the Work, or exergy input, is optimized to a minimum. In this case the source and sink temperatures are both close to each other, and what was the fixed anergy sink for the heat engine can now be utilized as the anergy source along with the heat sink in the heat pump to optimize the overall performance.

The thermal efficiency of the heat engine is defined as the ratio of work or exergy output to heat input, Equation (1). The maximum possible efficiency of the engine is defined by the 2nd law of thermodynamics by Carnot in Equation (2). This is defines the maximum available work, or exergy, coming from a heat source at temperature, \( T_{\text{Hot}} \), which interacts in a thermodynamic cycle with the environment at \( T_{\text{Cold}} \) as shown in Figure 4.2(a) and described in Equation (3). Exergy increases as the temperature of the heat source increases, and thus high temperatures are used in heat engines, while the reference environment can remain relatively fixed.

\[
(1) \quad \eta = \frac{W_{\text{out}}}{Q_{\text{Hot}}} \\
(2) \quad \eta_{\text{Carnot}} = \frac{(T_{\text{Hot}} - T_{\text{Cold}})}{T_{\text{Hot}}} \\
(3) \quad Ex = W_{\text{max}} = Q_{\text{source}} \cdot \eta_{\text{Carnot}}
\]

For the supply of heat using a heat pump, the efficiency is defined by the COP (coefficient of performance), or the ratio of heat output to work input in Equation (4). Again, the maximum performance is restricted by the 2nd law in Equation (5). Here, the maximum ratio of heat that can be provided per unit work input increases as the difference between the system temperatures, \( T_{\text{Hot}} \) and \( T_{\text{Cold}} \), decreases. The work input or exergy demand, can be minimized by reducing this temperature difference, or temperature-lift of the heat pump. Thus low temperature systems are used for low exergy building systems, and both the sink and the source temperatures play a role in the system optimization, complicating the view of the reference temperature.

\[
(4) \quad COP = \frac{Q_{\text{Hot}}}{W_{\text{in}}} \\
(5) \quad COP_{\text{Carnot}} = \frac{T_{\text{Hot}}}{(T_{\text{Hot}} - T_{\text{Cold}})}
\]
Considering anergy use for buildings

The method we use to reduce this complication involves considering the concept of anergy for the two systems in Figure 4.2. In the case of anergy, a heat engine must deposit a certain amount of heat into the reference environment in order to operate. This is required by the Kelvin Statement of the 2nd law of thermodynamics. The requisite amount of heat that must be deposited into the environment to operate the heat engine is defined as the anergy, Equation (6), or in other words the amount of heat input, or energy input, that can do no work and create no exergy. It must be dispersed into the reference environment to operate the engine. Therefore the anergy is also often defined as dispersed energy [4].

\[ An = Q_{source} - Ex \]

Based on this definition for heat engines, anergy has no inherent value, but again when we consider the case of building operation, we can leverage this concept of anergy in a different way to create new opportunities to optimize building systems. If we reconsider the heat engine, as shown in Figure 4.2, a change in the system temperatures actually changes the amount of anergy, or lost potential, that is generated. In this way, if the ambient temperature, \( T_{Cold} \), in Equation (2) decreases, the maximum work output, \( W_{max} \), and the exergy, \( Ex \), in Equation (3) also change (albeit only slightly), and thus the anergy, \( An \), in Equation (6) decreases. What was anergy under previous conditions is now exergy that has potential to do work.

It is using this method of thinking that allows the concept of anergy to be exploited for low exergy building systems design and optimization. Using this method, designers can be easily instructed to maximize the anergy source temperature. The generalization or grouping of the potential heat inputs as anergy sources for low exergy buildings is our method to facilitate better overall building system design as shown in the results of previous work and pilot projects [17-20].

The method of utilization of exergy and anergy flows

The concepts of exergy and anergy for low exergy building system has been shown to provide a rationale for low exergy design processes that account better for system temperatures to minimize exergy demand. However, it doesn’t account for the ambiguities in defining the reference environment, and quantifying the exergy from various heat environmental heat sources. For engines, the anergy sink provides a clear definition of the reference state, but by using the concept of an anergy source for buildings the reference state is no longer fixed, and there are both warm and cool anergy sources and sinks to consider, as seen in Figure 4.1(b) and Figure 4.2(b), depending on climatic and building conditions. In order to provide a result that describes the full picture of exergy and anergy use for low exergy building optimization, a new concept was built based on the methods described by Brodyanski [30] and illustrated by Shukuya and Hammache [4].

Brodyansky created a new term for exergy efficiency called the utilizable exergetic coefficient [30]. This term went beyond basic definitions and the rational exergy definitions made by Kotas [29]. It considered the concept of transiting exergy. The new concept was again created within the sphere of mostly thermal plant analysis, but it separates the exergy and anergy flow through a system into parts that are useful for creating an exergetic perspective for building design. The diagram in Figure 4.3 shows a representation of the concept from Shukuya and Hammache [4].
Using this concept, a utilizable exergy coefficient is defined, which is the ratio of the produced utilizable exergy to the consumed exergy. Within the system, the internal losses and external losses are quantified as well as the exergy that transits the system. This procedure is very helpful when part of exergy input is not utilized. If one looked solely at the heat flow through a hydronic heating distribution system, the produced utilizable exergy would only be the exergy transmitted to the emission system while the return flow to the heating system would just be transiting exergy. Both the produced utilizable exergy and the transiting exergy have potential to do work relative to the environment, and together they represent the total utilizable exergy.

For this analysis method, it makes more sense to choose one reference environment. If different states are defined for the heat generation, distribution, and emission systems, it makes comparing the exergy of these systems difficult. In the end, the full chain generates a utilizable exergy that provides a temperature and humidity gradient against non-ideal ambient conditions. Each subsystem has potential internal losses due to irreversibility, such as pressure drops, as well as potential external losses, such as from piping placed close to external surfaces where heat can be lost directly to the environment. Each system has a potential relative to the ambient conditions, even when contained in the building, and for an exergy analysis of an entire building, the actual utilizable exergy is what is provided to the space to maintain comfort. Comfort is maintained by managing the heat dissipation into the environment (the exergy utilization itself in the form of maintained thermal gradients). Therefore, the concept of utilizable exergy provides a rationale for the reference environment of for the entire building system to be made consistently at the ambient conditions in order to facilitate system optimization. From this framework, we have built our resulting concept for the utilization of exergy and anergy for buildings, which accounts for both the reference environment and the use of exergy and anergy in terms of various environmental sources and internal uses.

Results

Utilizing exergy and anergy for buildings

As stated above, the appropriate use of exergy as an element of building design requires a slightly different perspective. It is clear that a building operates under a wide range of...
conditions, which makes a consistent definition difficult. Therefore we propose a slight extension in the way in which we utilize the concept of exergy along with its counterpart, anergy.

We propose that exergy for building analysis be defined as the energy that has potential to do work with reference to the ambient environmental conditions, and furthermore that exergy inputs extracted from a dispersed state in the external environment can be referred to as an anergy sources. The reference state is then the state that acts as the final anergy sink for the utilized exergy in the building.

This statement means that all forms of raw exergy input such as combustion sources and electricity are evaluated as consumed exergy inputs with reference to utilizable exergy in Figure 4.3 [4, 30]. These processes along with the subsequent supply and distribution processes in the building are evaluated using the ambient outdoor conditions as the reference environment. We also go one step further and say that the exergy inputs that come from freely available sources that are part of the external environment can be called anergy sources. This is based on the concept of dispersed energy described by Shukuya and Hammache [3].

It follows that heat or anergy sources for heat pumps can be viewed as dispersed within their local environment. This is easy to understand for an air source system where the outdoor air represents the ambient outdoor conditions, but we extend this view for ground source systems as well as for seasonal storage. The only change that occurs is a movement of anergy out of a quasi-infinite reservoir where it is dispersed and into one where it has potential. This movement can be spatial (ground source) and/or temporal (seasonal storage). We also argue that this movement can also be an interception of flows on their way to being freely dispersed. This would be the case for radiation and waste streams on their way into the external environment, which can therefore be grouped representatively as anergy sources as well. When any of these anergy sources is brought into the building through spatial, temporal, or intercepted movement, it gains potential relative to the final anergy sink of the utilized exergy of the building, which defines the reference environment.

We have produced the resulting depiction in Figure 4.4 that expands on the depiction of Figure 4.3 to illustrate how this utilization of the concepts of exergy and anergy based on the fundamental ideas of Brodyanski [30] can be effectively applied to buildings. This provides a rationale for an exergetic efficiency for buildings that is based on the actual valuable inputs of primary energy verses the actual utilized exergy to provide comfort. It allows the free environmental sources to be accounted for while remaining external to the goal of exergy input minimization and effective final exergy utilization.
Figure 4.4: Expansion of the concept of utilizable exergy for buildings along with the application of transiting exergy as originating in sources of what would be or what are fully dispersed anergy. The grouping of anergy sources provide a unique perspective and helps heat pump optimization [3][10].

The analogies made in Figure 4.4 provide a new perspective of exergy analysis for buildings. The external environment becomes a black box. There are many potential anergy sources from the external environment, and there is one final sink where the utilized exergy is dispersed to maintain comfort after flowing out of the building into the reference environment.

This facilitates the grouping of free anergy sources coming into the building system, the consumed exergy in the form of delivered primary energy, and the final utilized exergy to maintain comfort. Anergy sources form the transiting exergy because they come from a free dispersed state and end in a dispersed state. It is then utilized along with the consumed exergy input to make up for internal and external losses and produce the final building demand for comfort. The anergy sources are only given potential within the context of the building. The anergy source evaluation allows for a minimization of temperature gradients and maximization of performance by reducing consumed exergy and thus primary energy demand. Typically building designers focus only on building thermal performance and reducing losses related only to the final utilizable exergy demand. The perspective presented in Figure 4.4 gives designers access to improvements through integrated low exergy concepts as well.

The true performance of the building is also clarified. The ratio of the utilizable exergy to the consumed exergy in Equation (7), gives a measure of performance that is very useful when trying to minimize primary energy inputs and subsequent CO₂ emissions due to building operation. It provides is analogy based solely on exergy concepts to the primary energy ratio (PER), which has been used previously along side exergy analysis by the Annex 49 [3] and by Kanoglu, Dincer and Cengel [31].

\[
\eta_{Ex,building} = \frac{E_{X,utilizable}}{E_{X,consumed}}
\]

This performance indicator can be improved by standard methods of demand reduction like addition insulation. But exploiting the concept of anergy sources can make even further improvements. Increasing the utilization of free anergy sources both decreases the consumed exergy and increasing the utilized exergy in Equation (7) and Figure 4.4. This can
have a dramatic impact on performance, and these are the steps needed to move toward zero emission buildings.

The climate conditions of the external environment into which the building directly interacts are used to define the reference environment. This is the final anergy sink of the utilizable exergy in the building, representing the final dispersed state in the ambient outdoor condition. Defining the reference environment allows one to view the exergetic performance of the system as a whole. Each subsystem of the building is operating within these bounds, and will have its exergy input and output defined based on the potential with reference to the ambient conditions. The result is a logical rationale for the development of a more universal methodology for exergy analysis of buildings. The utilizable exergy is the basis for the heating or cooling demand that must be supplied, and the consumed exergy represents the delivered primary energy that can be minimized through exergy analysis.

With this framework, the minimization can be achieved by both improvements in exergetic performance of subsystems, as well as by increasing the extraction and value (temperature) of anergy sources. Thus exergy analysis can independently optimize each aspect of building operation while these methods provide a potential basis for design and comparison of the entire system.

Applications of exergy and anergy for building design

The development of this concept has taken form from ideas used in course lectures and demonstrations by the ETH Zurich Building Systems Group [32]. Applications have been employed to help architecture students grasp the ideas of low exergy design without requiring extensive understanding of thermodynamics.

The IEA ECBCS Annex 49 has considered the applications of exergy and anergy as part of its objective to find a common definition of a reference environment, and hope it will stimulate further discussion, and ultimately move closer to consensus on the issue. The concept has thus far been a primary part of the work done by the viaGialla project and the related building projects [19, 20] Within these frameworks a variety of new technologies are under development and prototyping, which have been designed based on these concepts of exergy and anergy [15, 17, 33].

The design of buildings using this methodology allows for an initial optimization of the exergetic performance from concepts alone. Figure 4.5 extends the simple view of the building from Figure 4.1 to one that includes these concepts of exergy and anergy. The result is a better perspective of low exergy buildings for designers, which facilitates the utilization of these concepts to improve building performance.

Figure 4.5: An extension of the building system introduced in Figure 4.1 that incorporates the described utilization of exergy and anergy for buildings. The work input, $W_{in}$, is the consumed exergy, $\dot{E}_x^{consumed}$, input into the building. The utilized exergy, $\dot{E}_x^{utilized}$, maintains the comfort based on the
heat fluxes, \( Q_{\text{heat}} \) or \( Q_{\text{cold}} \). There are three types of anergy sources: spatially moved sources, \( \text{An}_{\text{spatial}} \), such as geothermal heat; temporally moved sources, \( \text{An}_{\text{temporal}} \), such as seasonal storage; and intercepted sources, \( \text{An}_{\text{int}} \), such as recovered heat or captured solar or wind. Systems that can be used to capture various warm or cool anergy sources are listed.

We reiterate that various states of local dispersion or states on their way to being dispersed can be captured as anergy sources through temporal, spatial, or intercepted movements. This range of spatial, temporal, and intercepted transient deviations of conditions within the external environment are potential anergy sources. They are sources that are or will be fully dispersed energy incapable of work locally, but that can be exploited through movement in the system using varying levels of quality. Such exploitation has been shown to have great potential to increase heat pump performance \([18]\) and leads to improved flexibility in architecture \([34]\). In this manner the primary energy demand can be independently reduced without depending on wall construction for heavy restriction of heat losses.

More recently this perspective has been taken up in the Swiss government and the Swiss media in the discussion about how energy efficiency standards in Switzerland should be further developed. The perspective we have presented of anergy sources providing offsets that are not considered by simple prescriptive insulation measures has led to the consideration of new policies within the standards. These would allow more flexible designs that consider the consumed exergy to operate the building, and not just the demand, or utilized exergy, to provide comfort. \([35-41]\)

**Outlook and Conclusion**

The argumentation for setting the reference environment to the external environment of a building has been presented. This follows from an adapted perspective of exergy and anergy utilization for more effective to the building design. The final goal is to provide a logical analysis of the desired exergetic output to be utilized in a building system compared to the exergy that is consumed to provide that output. From this perspective buildings are different from the heat engines that sparked the development of exergy analysis. Yet they are thermal systems that make exergy analysis appropriate, and a new perspective has been presented that helps reconcile this.

This proposal was inspired by discussion within the LowEx building community and further discussion will certainly be in order. More importantly, some comparison of the methods used thus far for exergy analysis of buildings and how our model that has been described can be incorporated. The method has been successfully implemented for several design projects, and has led to increased interest in low exergy design in the Swiss building community. Still more case studies and pilot projects are underway. At this point there is still much room for argumentation, and future discussion will hopefully lead to an even more uniform methodology for exergy analysis of buildings with a properly defined reference environment.

**References**


5 Integrated Low Exergy Systems

5.1 Overview and References

These papers present a broad picture of how a wider range of low exergy systems can be combined with a low temperature-lift heat pump to achieve potentially higher levels of system performance than have yet been achieved for in buildings.

Papers:

Clima 2010

Energy (in press)
5.2 **Context of Papers**

During the course of this research into specific systems and the concepts of exergy and anergy, there were many other systems being developed within the Building Systems group. With the high performance of a low temperature-lift heat pump with a COP up to 13 being demonstrated by collaborators at the HSLU in Lucerne [2], it became possible to demonstrate the very high potential performance of integrated low exergy systems.

This was presented first in a paper at the conference Clima 2010, titled “The missing link for low exergy buildings: Low temperature-lift, ultra-high COP heat pumps.” In this paper the ability of various low exergy technology combinations to achieve extremely high COP values is explored. Also, a comparison is made between the performance increases achieved by passive methods of adding insulation to a building versus the benefits of improving the active heat pump system. It is clear that striving to meet passive house standards can lead to potentially excessive material usage, and a good mix of active performance and passive resistance is the best solution.

A second paper was presented at ECOS 2010, titled “Low Exergy Building Systems Review.” It has been submitted to the journal *Energy*. This paper reviews the technologies that have been developed in the Building Systems group and discusses their integrated operation. The comparison between a heat engine and a heat pump for buildings is again emphasized to help describe the benefit of finding higher temperature anergy sources.

This research served as a kind of culmination of the fundamental work because it illustrated the great potential of the combined low exergy systems for the entire building. Some of the systems described could be further investigated with more in depth models, but these papers provide the description of how the complete system would look and could operate assuming certain technical obstacles are cleared. In the second paper, all the technology being described is being implemented in either the B35 building or the renovation of the HPZ on the ETH Zurich Hönggerberg campus. These provide real examples of how the technology is being implemented and will eventually serve to validate and evaluate the operation that has been described in this research. It shows how these concepts of low exergy systems can be integrated into a whole building.
**Paper 5.1: The missing link for low exergy buildings: Low temperature-lift, ultra-high COP heat pumps**

Forrest Meggers, Matthias Mast and Hansjürg Leibundgut


**Summary**

Low exergy buildings employ heating and cooling systems that match the building’s energy requirements to an energy source of optimal quality. It does not make sense to use high-temperature combustion (high-quality energy) to heat a room to 20 °C. Alternatively, a heat pump is an appropriate low exergy technology that exploits renewable, low-value heat sources. When the heat source (ground, water, solar, waste-heat) is relatively close to the heating supply temperature, very large amounts of heat per unit electricity can be moved. This efficiency is derived from the direct relationship between heat pump performance (COP) and temperature-lift. The key to realizing the benefits of low exergy systems lies in low temperature-lift, and the subsequent ultra-high COP that heat pumps can provide. As more low exergy systems enter the market, the potential for these heat pumps grows. In our research we present this potential and demonstrate how this active concept outperforms popular passive techniques.
Introduction

The heating and cooling systems of buildings have been the focus of many optimization strategies for reducing building energy demand. Most have focused only on the simple energy balance of the building. This leads to systems like the passive house, where the heating demand is reduced to virtually zero, but the construction and aesthetics are subsequently very constrained. By using the concept of exergy to evaluate the building performance, these constraints can be lifted [1].

For example, what if a device the size of a shoebox could take 100 W of electricity and produce 1 kW of heating? This technology is being researched in various collaborations at the ETH Zurich for the development of small heat pumps with COP greater than 8, thus providing more than 8 units of heat per unit primary energy input. This is driven by the potential of low exergy systems with integrated heat pumps needing temperature lifts down to 10K and lower, which would have potentially much higher COP values. A COP of 11 has already been experimentally achieved by collaborators in Lucerne, Switzerland for a full-scale heat pump with temperature lift of 15K [2]. We present a wide variety of low exergy building systems that can minimize temperature lift to this level and lower, which drastically reduce primary energy demand. This is achieved using active technology that maximizes the exploitation of free environmental heat sources. We contrast this with the performance of passive systems that focus on maximizing the barrier to the external environment to minimize heat loss. We prove active principles can achieve much higher and more flexible performance than passive designs. Finally, we will present some pilot projects where these ideas are beginning to be implemented.

Methods

Exergy Concept and Heat Pump Analysis

Exergy is a concept developed from the 1st and 2nd laws of thermodynamics. It combines an energy balance and an entropy balance to generate a new term that accounts for both aspects of energy quantity from the 1st law and aspects of quality influenced by the generation of entropy from the 2nd law. Instead of using some absolutely defined value of energy, exergy analysis evaluates an available amount of work that can be done by a system when it interacts with its surrounding environment. This depends on the absolute quantity of energy and its temperature. The higher the temperature of a system, the more potential it has. The use of the 2nd law and exergy for building system analysis has been described by Schmidt [3].

The performance of heat pumps is similarly based on the 2nd law of thermodynamics. In this case the thermodynamic cycle that a heat pump uses is limited by the 2nd law to a certain maximum performance, which is fixed by the temperatures of the system. The input into the cycle is in form of primary energy, usually in the form of electricity to run a compressor. This input runs a cycle that moves heat from a source like the ground to a sink like a building, or vice versa for cooling. The amount of heat moved is a function of the coefficient of performance (COP) of the heat pump, which is the ratio of heat moved, $Q$, to electricity input, $W$, as in $COP = Q / W$. This number is often cited as a fixed value like lightbulb efficiency, but in fact this number is less dependent on the machine itself, than on the system temperatures it operates with. The maximum value of the COP for heating, $COP_{\text{ideal}}$, is the ratio of the heating temperature in Kelvin, $T_H$, to the temperature difference, or temperature-lift, $T_H - T_C$ that the heat pump provides from source to sink. The real COP of a
heat pump, $COP_{\text{real}}$, can be defined using a Carnot factor that defines the ratio between the maximum performance and the real performance as shown in Equation 1 and 2.

$$COP_{\text{ideal}} = \frac{T_H}{T_H - T_C} \quad (1)$$
$$COP_{\text{real}} = \eta_{\text{Carnot}} \frac{T_H}{T_H - T_C} = \frac{Q}{W} \quad (2)$$

This Carnot factor for heat pumps is more directly related to the machine performance than the COP, but unfortunately often only the COP is considered when comparing systems. The system design should consider how the temperatures within the system directly impact the COP, and thus the ratio of heat production to primary energy consumption. We use this simple and well-known aspect of heat pump COP to demonstrate how low-temperature lift heat pumps can drastically reduce primary energy demand. We demonstrate this using the illustration shown in Figure 5.1. At temperature-lifts below 20 K, the COP of a heat pump increases rapidly, and can be provided by low exergy systems.

**System Analysis**

We describe a variety of low exergy systems that can be combined to achieve temperature-lifts below 20 K. The potential performance is tabulated based on the heat pump performance shown in Figure 5.1. This assumed Carnot efficiency of 0.5 was achieved experimentally by Wyssen [2]. The performance for each individual combination is tabulated, demonstrating the large potential for various options. Also, just as refrigerators have become ubiquitous in buildings (with most containing 2 or more compressors, and many buildings contains more than 1 unit), so too could low-temperature-lift heat pumps be miniaturized and distributed. These could then operate with different optimal temperature-lifts for various services from heating to hot water production to cooling, all exploiting thermal sources from waste-heat to daily or seasonal storage. This distributed potential could be developed eventually, with some new distributed pumping systems already being piloted [4], and would maximize the flexibility of operation of the entire active system concept.

![Figure 5.1: Plot of heat pump COP versus temperature lift assuming a typical Carnot factor of 0.5. The curve flattens out in the 20-40 K range of typical heat pumps and shows why COP values are usually cited as relatively constant performance factors. Below 20 K the potential COP rises rapidly.](image-url)

In order to make a comparison between the active low exergy systems and a passive insulation system, we assume a generic building construction. A generic 2-story building is assumed with height of 7 m, length of 12 m, width of 8 m, and a typical concrete structure of
20 cm thick walls. The insulation of the walls is assumed to be EPS or equivalent with a thermal conductivity of 0.03 W/mK and the thickness is varied to analyze the impact of increased insulation. This building is analyzed for heating demand and required peak power, both normalized by floor area, using weather data for Zurich, Switzerland.

After highlighting the differences between passive and active performance we have selected a few case studies to demonstrate the application of some of these concepts in practice. We have chosen some buildings that are completed, some designed, and some conceptual projects that have improved performance due to the integration of low exergy supply systems and heat pumps. The concept of ultra-high COP, low temperature-lift heat pumps is still under development, but many low exergy technologies are already available and they are presented here in various examples.

Results

Low Exergy Systems

We have developed a wide range of low exergy systems that are in production as well as concepts that are under development. They include both systems that reduce heating supply temperatures, and systems that exploit potentially high-temperature sources. These are grouped into low exergy supply and anergy sources. Low exergy supply systems use low-temperature heating and high-temperature cooling to minimize exergy destruction in heat transfer while maximizing heat pump performance. We use the term anergy, thermodynamically defined as dispersed energy, as an analogy to define the freely available heat sources and as a representation of the heat input into the heat pump that comes from the environment.

Low Exergy Supply

A simple energy balance defines the quantity of energy needed to maintain comfort in a building. But the temperature of the system is only limited by its design. By using systems that take advantage of larger surface areas in rooms, lower temperature systems can be achieved. This can easily be achieved with panels on the ceiling or by integrating heating into the floor. Our ceiling panel system, at only 30 °C, can supply around 50 W/m² of heating [5]. These systems can be easily supplied with water or some other working fluid that can be pumped efficiently through the buildings compared to forced air heating or cooling. The lower supply temperature also reduces losses in the distribution system. The same is true for the cooling case, where adequate cooling can be provided at a temperature of 18 °C.

Another technology that results from our method of low exergy system design is decentralized supply ventilation. This system supplies demand-controlled air to a building directly through a façade using small decentralized ventilation systems. These use small heat exchangers using the same fluid temperature at the ceiling panels to provide air at a minimum of 18 °C. This not only minimizes the exergy loss from high temperature centralized air conditioning, but it also eliminates the losses from large pressure drops in air distribution networks. Again, the working fluid can be more efficiently pumped to distribute the low temperature heating. In the cooling case they may need to utilize a lower temperature around 10 °C for dehumidification, but this should be possible with very low temperature-lift cooling operation, and with properly managed cold storage it might still be directly provided.
Finally, our design paradigm leads to new ways to think about how we provide hot water in buildings. When we consider exergy the high value of hot water becomes obvious. The heat capacity and temperature of water make a hot-water storage tank a large exergy store. Why then do we produce our hot water at 55-60 °C when most hot water usage is at 40 °C or below? We have designed a new hot water system that stores water at the average usage temperature instead of the maximum temperature demand. Any demands for higher temperatures can be provided with supplementary heating systems. The typical strategy of supplying hot water at the maximum temperature destroys large amounts of exergy because of storage and distribution losses and the typical mixing that takes place at the point of use.

Anergy Source

While reducing the temperature of hot water production helps reduce the exergy destroyed when it is used, the warm wastewater that goes down the drain also has a large potential, and again it is concentrated due to the high heat capacity of water. We have designed a new heat recovery system for warm wastewater that has been optimized for maximal exergy recovery from the waste stream [6]. This provides a higher temperature source that can be used to maintain a low temperature-lift during hot water production. The temperature of warm water heat recovery is often lower due to mixing, but our system extracts heat over a time period immediately following use such that mixing with cold wastewater is minimized. Also, when ecological systems like grey water recycle or low-flow toilets are implemented, the cold-water flow is eliminated or greatly reduced, increasing the exergy content of the recovery.

Recovery from exhaust ventilation is a more common practice, but one that should not be overlooked in low exergy system design as well. The exhaust ventilation is collected through our ceiling panel system. The exhaust ventilation ports are operated based on CO2 sensors to optimally extract air from locations where it is most contaminated. This has been shown to be able to reduce the fan power needed to provide clean healthy air [7]. For heat recovery there is lower capacity due to the low density of air. Nevertheless, this provides another source of around 20 °C to augment heat pump source temperature, and this is available almost continuously form the centralized exhaust network. Also, a new concept is under development to utilize the excess fan capacity of external exhaust fans during non-peak periods as an air heat exchanger to extract or dissipate heat for seasonal regeneration of ground boreholes.

These ground, or geothermal boreholes are central to the low exergy system for supplying better source temperatures to heat pumps. We have designed a new dual-zone borehole system in which two vertical boreholes are drilled to different depths. One is drilled very deep to ~300 m, where the geothermal temperature gradient (usually 1-4 K per 100m) increases the ground temperature to create a warmer reservoir. Then a shallow borehole accesses the cooler average seasonal temperature. In Zurich, Switzerland this system creates one thermal reservoir with a temperature of ~8 °C and one of ~15 °C that can be used for cooling and heating as base-load sources for the heat pump. Also, the separate boreholes create two reservoirs that can be independently recharged for seasonal heat and cool storage, eliminating the challenging requirement of balancing demand for seasonal storage.

A final innovation that we have integrated into our package of potential low exergy systems is a new hybrid photovoltaic thermal collector (PVT). Again we recognize here the importance of matching the temperatures utilized by the building and the temperatures
The missing link for low exergy buildings: Low temperature-lift, ultra-high COP heat pumps

generated. By installing a very simple heat exchanger on the back of new inexpensive solar panels, waste heat can be collected from the cell during sunny periods at temperatures easily from 30-35 °C if not higher. First Solar has already brought manufacturing cost below $1 per Watt in 2009 [8], reaching near grid parity, and OC Oerlikon in Switzerland predicts costs of $0.70/W by the end of 2010 [9]. Both companies achieve this with cells with efficiencies of approximately 10% or slightly higher, and by actively cooling the system the efficiency could be increased. Still the efficiency may seem small compared to monocrystalline cells, but by extracting the heat from the system the solar energy utilization is increased, and if the Watts of heat extracted are added to the system, the price per Watt drops even further. On top of that, unlike thermal-only collectors, the heat collection comes directly from the surface instead of in vacuum tubes, which allows for direct use of sky temperatures for irradiator cooling at night.

Heat pump performance

The combination of these technologies provides the potential for very high system performance. Table 5.1 gives the heat pump performance based on Figure 5.1 for the supply and source systems given above. It also demonstrates the potential options for recovery of any source excesses to regenerate the warm and cool borehole reservoirs.

<table>
<thead>
<tr>
<th>Systems</th>
<th>Dual-Zone Borehole</th>
<th>Waste Heat</th>
<th>PVT</th>
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<tbody>
<tr>
<td></td>
<td>Temps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating</td>
<td>30 °C</td>
<td>Warm 15 °C</td>
<td>COP=15</td>
</tr>
<tr>
<td>Hot Water</td>
<td>40 °C</td>
<td>Cool 8 °C</td>
<td>COP=15</td>
</tr>
<tr>
<td>Cooling</td>
<td>18 °C</td>
<td>Exhaust 20 °C</td>
<td>COP=8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wastewater 30 °C</td>
<td>COP=15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heat 30 °C</td>
<td>Direct</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cool 0-20 °C</td>
<td>Direct</td>
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<tr>
<td>Warm Recharge</td>
<td></td>
<td>Summer</td>
<td>All-year</td>
</tr>
<tr>
<td>Cool Recharge</td>
<td></td>
<td>Winter</td>
<td>All-year Nights</td>
</tr>
</tbody>
</table>

When a heat pump is able to operate with such high COP values, the amount of electricity needed to operate the compressor becomes very small. This makes it much easier to supply this electricity with renewable sources. The area of photovoltaic panels needed to generate the heating energy is greatly reduced. Even with hybrid PVT panels with an efficiency of 10%, if heat supplied at 30 °C allows operation with a COP of 15 as in Table 5.1, then 150% of solar energy converted to electricity will be supplied as heat, making any thermal panel obsolete.

Comparison of active versus passive

The use of low exergy building systems allows for low-temperature heat pumps to be implemented that can achieve very high performance. This design method is contrary to typical passive design techniques. By combining these active systems, the actual primary energy demand is greatly reduced independent of changes in the heat demand of the building. Contrarily, passive systems only reduction method is to reduce heat demand directly. This includes methods such as heat recovery, but depends heavily on increased insulation and therefore wall thickness and material.

The marginal return of the final cm of insulation for a passive house is actually quite insignificant. The peak heating power demanded for design conditions in Zurich as well as the annual heating demand per square meter of our generic model building are shown in Figure 5.2 for a varying amount of insulation. Also plotted is the typical performance limit...
for a passive house standard. Finally, the annual energy demand of a heat pump is included assuming an average COP of 10.

In order to reach the level of a passive house for peak power demand, 15 cm of insulation is needed and for the annual energy demand, nearly 30 cm of EPS or equivalent insulation is needed. Also, observing the benefits as more insulation is added, it is clear that there is not much additional benefit for the final amounts of insulation needed to meet passive house standards.

Compare this to the annual energy demand of an ultra-high COP heat pump. The heat pump demand is lower than the passive house annual energy demand standard already at 1.4 cm of insulation. Granted, all that heat demand is still supplied by the heat pump, but only 1/10th is primary energy as shown by the thick green line in Figure 5.2.

The passive design concepts lead to a focus on isolating the building from the environment. By using a heat pump and low exergy systems we have maximized the integration of the building with the environment. It is clear that insulating much beyond 5 cm in Figure 5.2 does not provide significant payback, and with an active heat pump system the primary energy demand is already very low at this point, over half of the passive house standard. With active systems building designs are less restricted by thick-walls and usable space is increased relative to the building footprint. Also a wider range of lightweight, deconstructable and recyclable/reusable materials can be implemented in active designs as compared to passive houses that have large ecological footprints and grey energy/emissions in construction [10].

In fact, the only limit to our active system is the ability to supply enough heat using the low temperature heating. Assuming the ceiling panel can use the surface area of the ceiling, being approximately equal to the floor area, the limit of 50 W/m² can be reached with less than 2 cm of insulation as shown in Figure 5.2. Even with half the surface area active on the ceiling, 5 cm of insulation should be enough to cover the peak heating power demand, and at this level of insulation a good heat reduction per cm used is still achieved, while maintaining a thin construction.
Case Study Examples

The performance of our complete low exergy system with low temperature-lift ultra-high COP heat pump is still theoretical, but most of the individual systems have already been implemented in a variety of building projects, and are being refined and improved. As we move toward the development of ultra-high COP heat pump technology, the low exergy systems still improve building performance greatly with currently available heat pump technology.

Advanced heat pump systems have been implemented for example in the A&W headquarters building in Zurich [11], the Eulachhof multifamily development [12], and in the HPZ renovation project [4]. The A&W building utilizes a dual-compressor heat pump system that achieves a COP of 5.3 and incorporates exhaust air heat recovery. The building was also an initial pilot of the decentralized air supply system. In the Eulerhof development a heat pump is installed that supplies both heating and hot water. In this case exhaust heat as well as heat from wastewater are recovered. Both of these projects have PV installed on the roof that would have had the potential for PVT operation, but this concept is still in the early development phase. At the HPZ a test heat pump has already been installed and is being operated in conjunction with two test rooms where the ceiling panel and decentralized air supply systems are being tested [4]. This is being used to optimize and prove the potential of the planned low exergy renovation beginning at the end of 2010.

A major low exergy pilot project underway is the B35 project in Zurich [13]. This building will be the first to incorporate the dual-zone borehole system. It will also be the first to utilize the low-temperature hot-water system. More importantly, the first pilot installation of hybrid PVT panels will be installed on the roof, which will be important in the regeneration of the warm borehole as well as a high-temperature heat source for hot water production. Ideally a heat pump will be installed that can operate with a COP of about 8.

Discussion

We have shown how a low temperature-lift heat pump can achieve an ultra-high COP and when realized, will be the key to very high performance integrated low exergy building systems. These systems lift the restrictions placed on designs by high performance passive methods by utilizing active systems that focus more on exergy consumption and primary energy demand. We have developed new technologies for renewable resource utilization by grouping the options for extracting dissipated low value heat, or potentially wasted and dissipated heat as anergy sources. These anergy sources are connected to our low-temperature-heating/high-temperature-cooling supply systems through a heat pump with minimal temperature lift. We have shown how these combinations lead to a very high performance. With such high COP values, the primary energy supplied to the heat pump becomes easily achieved with renewable energy production from sources such as hybrid PVT.

The main assumption in this review is that the heat pump performance can be maintained down to low temperature lifts. Research is underway to test the potential of heat pumps at low temperature-lifts [3], and the Carnot factor does decrease slightly, but this will be addressed in future heat pump development. Thus, work will continue at the ETH Zurich and the HSLU in Luzern on a new small low-temperature lift heat pump. Also, further low exergy technologies will be designed, and in collaboration with industry they will be installed in building projects to continue to increase building performance and move toward zero CO₂ emission buildings.
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References

**Paper 5.2: Low exergy building systems implementation**

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**Abstract:**

Low exergy (LowEx) building systems create more flexibility and generate new possibilities for the design of high performance buildings. Instead of maximizing the barrier between buildings and the environment using thick insulation, low exergy systems maximize the connection to the freely available dispersed energy in the environment. We present implementations of LowEx technologies in prototypes, pilots and simulations, including experimental evaluation of our new hybrid PV-thermal (PV/T) panel, operation of integrated systems in an ongoing pilot building project, and cost and performance models along with dynamic simulation of our systems based on our current office renovation project. The exploitation of what we call “anergy sources” reduces exergy use, and thus primary energy demand. LowEx systems provide many heating and cooling methods for buildings using moderate supply temperatures and heat pumps that exploit more valuable anergy sources. Our implementation of integrated LowEx systems maintains low temperature-lifts, which can drastically increase heat pump performance from the typical COP range of 3 to 6 to values ranging from 6 to 13.

**Keywords:** Buildings, Exergy, High Performance, Energy Efficiency, LowEx, Heat Pump
Introduction

Exergy

The concept of exergy was developed in the middle of the twentieth century as a tool to optimize the performance of thermodynamic machinery. Originally, the concept primarily applied to thermal plant analysis for minimizing heat flows that do not generate utilisable work, thereby producing valuable output. The creation of the term exergy [1], which is a combination of the energy balance of the first law of thermodynamics and the entropy balance of the second law of thermodynamics, made this aspect of performance analysis possible. The combination helps define directly the potential of a system to produce a useful output while interacting with its surrounding environment. The limits defined by Carnot, to which all thermodynamic cycles are constrained, are inherently considered in exergy analyses. Exergy quantifies the net potential of a system as influenced by both the quantity of energy available, as well as the temperature, or quality, available relative to the system's surroundings. The concept is detailed in several textbooks [2-4].

When a system is at the same thermodynamic state as its surrounding environment, it does not have potential to do work. Thus it has zero exergy. As a thermodynamic system moves toward equilibrium with its surroundings, a part of that change in state can be extracted as work, and part of the energy is dispersed. This flux of energy to a dispersed state generates entropy, or in terms of exergy analysis, it implies the destruction of exergy and the generation of anergy. Carnot and Kelvin proved that a certain amount of energy must flow to a cold sink for work to be extracted from a thermodynamic cycle. The maximal amount of work that can be extracted is then directly linked to this temperature gradient. In this way exergy provides us with a tool to better evaluate the value inherent in heat fluxes occurring across different temperature gradients. For example, the exergy content, $Ex$, of a heat flux, $Q$, going into a room at temperature, $T_{hot}$, compared to the outside reference temperature, $T_0$, is defined as $Ex = Q(1 - T_0/T_{hot})$. Therefore for small temperature differences, the exergetic value of heat flux can easily be less that 10% of the energetic value. For this reason it is interesting to look for sources with similar exergetic value to provide heat to our relatively low temperature buildings.

Exergy for building systems

More recently, this concept of exergy has been extended into the field of building design with the IEA ECBCS Annex 37 and then subsequent Annex 49 [5,6]. Torio has presented a review of exergy analysis applied to buildings [7]. The importance of the reference environment for exergy analysis of building systems has been analyzed [8,9], and the importance of exergy for overall environmental impact assessment has also been demonstrated [10]. In the Building Systems Group at the ETH Zurich we have extended the utilization of exergy and anergy for the analysis and development of building systems [11]. Our extension considers the difference between a heat engine, for which exergy was originally developed, and a heat pump, which is the core of our low exergy systems. The two systems are compared in Figure 5.3. In order to maximize the work output of a heat engine, the exergy output is maximized while the anergy is minimized. The maximization is limited by the Carnot efficiency of a heat engine operating between a heat source and anergy sink, $\eta_{Carnot} = W_{max}/Q_{in} = (T_{hot} - T_{cold})/T_{hot}$. In order for the heat engine to operate, some heat must flow to the cold source according to the Kelvin statement of the 2nd law of thermodynamics. Thus there is a limit to the efficiency, which is based on the engine operating temperatures.
In order for the heat engine to operate, some heat must flow to the cold source, and thus there is a limit to the possible efficiency, which can be increased by increasing the temperature difference between hot and cold.

**Figure 5.3:** The heat engine represents the origin of exergy analysis and the heat pump represents a principle component for exergy analysis of building systems. For both, the performance is dependent on the temperature difference between hot and cold.

When we consider the heat pump, which is just a heat engine operating in reverse, the limit is in how much heat can be provided per unit input of work, or exergy, defined as the coefficient of performance (COP). When a heat pump is set up for heating, it moves heat from what we define as an energy source to a heat sink (i.e. the building). The maximum amount of heat per unit work input is also limited by a Carnot value of the COP, as in \( \text{COP}_{\text{Carnot}} = \frac{Q_{\text{max}}}{W_{\text{in}}} = \frac{W_{\text{in}}}{(T_{\text{hot}} - T_{\text{cold}})} \). Here instead of maximizing exergy output, our goal is to minimize exergy input while maximizing heat output, and the COP is increased in this case by decreasing the temperature difference, or temperature-lift, that the heat pump must provide. As shown in Fig. 1, the heat output is just a combination of exergy and energy inputs, \( Q = E_{\text{in}} + A_{\text{in}} \). As stated, the heat output is controlled by the COP, \( Q = \text{COP} \cdot E_{\text{in}} \), where \( E_{\text{in}} \) is the electricity input for a vapor compression heat pump multiplied by the COP to achieve the required heat output, \( Q \). Therefore, the fundamental goal of providing heat with a minimal amount of exergy input can be achieved by maximizing the heat pump COP, which is accomplished by minimizing the temperature-lift. As a result of increased COP, the fraction of heat coming from energy sources increases. Therefore we must find sources of sufficient quality, as well as with large enough quantity, facilitated by considering freely available environmental energy sources, as well as sources of waste heat from the building that would otherwise be lost to the environment [11].

By maximizing the energy source temperature while minimizing the heat supply temperature we achieve our low temperature-lift system. There are many potential sources of heat around a building that have more potential than the commonly used source of ambient outside air. These potentials may be due to variations in the location of heat sources. For example, the heat below the ground or in a local body of water may have higher potential (i.e. temperature), and seasonal changes in temperature provide higher value sources that can be exploited with appropriate technology, as described in previous work on energy sources [11, 12]. This is complemented by systems that utilize lower temperatures in the building to supply heat, which is made possible by increased heating surface area, for example from activated thermal mass. These low temperature radiant systems have also
been shown to provide more comfort [13-15]. Such systems can be further optimized by an exergy analysis of the supply chain. Software tools have been developed and implemented that evaluate exergy destruction in building heating supply chains [16-18]. The data generated is used to reduce the amount of energy that must be supplied as well as the temperature at which it is supplied, thereby reducing exergy demand. Combining supply system exergy analysis and energy source evaluation results in a system with low temperature-lift and a very high COP. The system has the potential to provide a large amount of heating with little exergy input. We illustrate the potential COP for a heat pump in Figure 5.4.

![Figure 5.4: Variation of COP with decreasing temperature-lift. Below temperature-lifts of 20 K the COP increases rapidly. A typical range from ε=0.4 to 0.6 for exergetic efficiency for existing machines are illustrated.](image)

Finally, it is important to note that heat pumps can also operate as chillers. The performance is again limited by the temperature-lift, but this time operating with a different goal. In this mode, the desired function is the removal of heat, or in other words the supply of cool exergy, as described by Shukuya and Hammache [14] and recently by Jansen [19]. Cool exergy is provided as heat is removed into an energy source. It is often possible to find energy sources with adequate temperatures for direct cooling. These include the ground or night cooling, but one major obstacle is finding methods to supply adequate dehumidification and its potentially large latent heat demand. As long as humidity can be controlled, radiant cooling can take advantage of the same low temperature heating supply structures, utilizing higher temperatures that reduce supply structure temperature gradient, and thus reducing the temperature-lift for the heat pump providing the cooling.

We present an overview of the low exergy systems that we have developed based on our methods of building exergy utilization analysis and energy source evaluation [11]. The systems are in various stages of design and development, but the majority of the components are being piloted in the B35 building project currently under construction in Zurich. The systems are also playing a central role in the ongoing renovation of the HPZ building and in the design process for the new HIB building on the ETH Zurich campus [20, 21].
Technology Summary

As described, the heart of the system is a low temperature-lift heat pump system. Currently, the ultra-high COP heat pumps that have been demonstrated [22], and that have been shown to produce very high performance with integrated low exergy systems [12] are not commercially available. Therefore developing these systems is the focal point of ongoing research between ETH Zurich and HSLU Luzern. Operation with a COP higher than 13 has already been demonstrated while maintaining g-value greater than 0.5 at temperature-lifts below 20 K [22]. There is a long history of trying to maximize heat pump performance using exergy analysis [23-25], but we strive to integrate new building technologies that achieve even higher levels of performance.

The technology that provides the primary source for the heat pump is a new dual-zone borehole. Conventional borehole configurations provide one average temperature for heating and also for cooling that overlook the potential of the thermal gradient in the ground [26]. The dual-zone borehole provides one warmer deep u-tube of approximately 400 m with its shallow section insulated, and a cooler shallow u-tube of approximately 50-150 m. The main advantage of this borehole design is the decoupling of the deep and shallow u-tube, which allows simultaneous loading and unloading, resulting in more controllable seasonal heat storage. The control helps increase the heat source temperature, and optimizes the heat pump performance during the heating season by minimizing the heat pump temperature lift. The temperature optimization is further accomplished with activated thermal mass, which maximizes heating or cooling surface area and minimizes temperature gradient needed to supply heat to the room, and thus minimizes the temperature-lift.

Higher temperature demands, such as for warm water production, are achieved with a low temperature-lift using source heat from a hybrid Photovoltaic-thermal (PV/T) panel that we have developed. Unlike PV-only or solar thermal collectors that try to produce temperatures warm enough for direct hot water production, we combine the two and collect electricity along with lower temperature heat. Even at a lower temperature than typical solar thermal systems, the heat is still valuable for our systems at around 35°C. It can be used directly or help maintain a high COP for hot water production. In case of a lack of sun, the warm wastewater can also be captured in an insulated tank and act as a secondary higher temperature source for hot water production as has been demonstrated in previous work [27]. We have also developed new methods of active insulation that use ground heat directly instead of through the heat pump [28]. The reduction in price combined with the miniaturization of technologies has helped us develop decentralized air supply systems [29] that can capture wind loadings [30], as well as small decentralized pumps [31] that maximize flexibility of operation. The active components make the building operation steerable, and reduce the material demand and subsequent embedded greenhouse gases, especially for refurbishment [32]. The benefits from integrated low exergy systems make primary energy demand very low. The smaller demand is easily met by renewable sources such as the PV/T panels.

Based on the potential of the heat pump as a core component, we have developed a new integrated concept to minimize the required temperature-lift for all aspects of building operation. These systems minimize primary energy demand, which is achieved without excessive building shell insulation and fenestration requirements, which makes the architectural design more flexible while maintaining very high performance. Refurbishment projects of heritage buildings with prestigious facades get particular benefit from an
approach that goes beyond thermal insulation of the building envelope. The resulting technologies create an active approach to building efficiency as opposed to a passive one.

Our analysis includes a detailed description of how these systems are implemented in pilot building projects and the benefits. We also present the experimental results of the performance of our PV/T panels. We use the PV/T performance in a simulation comparing the integrated LowEx system, including the PV/T and dual zone borehole, with a more typical non-LowEx installation. Finally, we consider the investment costs in these active systems versus investments in passive insulation.

**Methods**

**Technology Integration and Evaluation**

Figure 5.5 shows how these technologies can be integrated into a building design. The systems are shown on a schematic of the B35 project [20, 21], which is where many of new low exergy systems are being piloted. The illustration demonstrates how the systems are integrated into one low exergy system, which provides mutual benefits to each technology.

![Figure 5.5: Schematic of a low exergy system integrated into a building. The various components are illustrated: (a) Exhaust heat recovery, (b) PV/T hybrid panels, (c) dual zone boreholes, (d) high COP heat pump, (e) low temp hot water storage, (f) warm wastewater heat recovery.

Heating and cooling are supplied to the structure from the heat pump, Figure 5.5 (d), connected to the dual-zone borehole Figure 5.5 (c). The dual zone borehole is dug and two different length u-tubes are installed for optimal heat recovery. The B35 project has one shallow u-pipe of 150 m for cooling and another of 380 m with the first 150 m insulated for heating. The system is connected over a series of switching valves to supply the heat pump, or to access directly the other heat supply and recovery systems.

Ceiling panels can be attached to activate the thermal mass or the concrete structure can incorporate a hydronic system as in Figure 5.5 (g). The use of ceiling panels allows for the centralized collection of exhaust air for heat recovery, and it has been demonstrated that the ports can be controlled by CO2 sensors to optimize air supply and contaminant removal [29]. The exhaust is centralized and assisted by natural convection to exit through the roof,
Figure 5.5 (a). Here the heat can be removed to a lower temperature by traveling through a heat exchanger to recover the heat back into the heat pump system.

The decentralized air supply system, Figure 5.5 (h) utilizes the concrete structure to supply air through networked ducts integrated into the form, which eliminate pressure losses from centralized ducting systems [33]. Wind loading on the façade can also be exploited by the decentralized system to minimize fan power [34]. There is no need for a plenum space so there are significant gains in height between the floors, benefiting design. The decentralized air supply units also utilize the same hydronic loop to condition the incoming air. The hot water heat is stored at a lower temperature in a tank in the basement that provides direct heating through an efficient heat exchanger, Figure 5.5 (e), and heat from warm water usage can be captured for heat pump operation, Figure 5.5 (f).

**PV/T Prototype Evaluation**

We evaluated our PV/T panels mounted on the roof and connected to the hydronic loop as shown in Figure 5.5 (b). The system can be connected to the heat pump to supply heat for hot water production, it can be connected directly to the heating system, or it can be connected to the borehole for regeneration. We have developed prototype PV/T panels at the ETH Zurich. These were initially tested at the HPZ building. A simple pipe installation was installed to allow water to collect heat from and provide cooling to the panel backside. The heat removed and the ambient and panel temperatures were monitored. The experimental setup is pictured in Figure 5.6. With this setup different conditions were observed as the weather varied on the rooftop.

![Figure 5.6: Experimental setup for the PV/T panels setup on the roof of the HPZ building, front (a) back (b). The panels were cooled with an experimental heat pump setup and the heat output from the system was measured during a variety of outdoor conditions.](image)

Another panel prototype was sent to the solar testing center, SPF Rapperswil, to have standard thermal and photovoltaic tests applied to it. A 1.6 m² collector was tested with a 33% glycol water working fluid and an ambient temperature of around 22 °C. The panel was tested for thermal performance with still air and with 3 m/s convection current to simulate wind. It was also tested both with the photovoltaic electric load active and inactive.

**Building Simulation**

We investigated the potential of low exergy components by setting up a simulation of a building with a structure based on the HPZ at the ETH Zurich [20, 21], which is currently being renovated using a low exergy approach. A simplified model of the HPZ was connected to the building systems using TRNSYS. We ran an annual simulation for the continental
climate of Chicago. Chicago was chosen for its large variation in summer and winter conditions to observe the seasonal storage capacity of system.

As in the actual renovation, the opaque part of the original façade is kept and only the thermal resistance of the roof and glazing of the windows were exchanged. The building systems were upgraded to LowEx building systems. This includes a low temperature lift heat pump with a constant g-value of 0.5 across operational temperature lifts, a double zone borehole field consisting of 14 boreholes (100m/400m), and a 450 m² array of PV/T elements in 15 parallel series of 26mm heat exchanger piping with 93 m of length per series. The PV/T installation corresponds to slightly more than half the roof surface. For comparison, the same building was modeled with a conventional energy efficient renovation where the façade was insulated with 10 cm of additional EPS insulation, and standard double u-tube boreholes of 200 m depth were installed in a field of 19 to have a similar effective length as the low exergy dual zone field. The same heat pump as in the LowEx model was used to demonstrate the effect of temperature lift shown in Figure 5.4.

Finally, we also compared the additional benefits versus the costs of the advanced dual zone borehole thermal storage. The general economic benefit of ground source energy has been demonstrated based on capacity [35], but has not focused on temperature benefits. The main purpose of a deep borehole in Figure 5.5(c) is providing heat with a higher temperature to reduce the exergy demand for operating the heat pump in Figure 5.5(d). Thus, the investment for installation of a deep borehole needs to be balanced with the passive building components that increase thermal resistance and reduce the annual heating and cooling demand. It is possible to relate the additional borehole length to the reduction of exergy demand, and also to relate the additional thermal insulation of the façade to the reduction of the annual heating demand. Since the costs per additional centimeter insulation and cost per additional borehole length are specific, one can determine the total costs caused by a certain thickness of insulation versus the total costs for a certain depth of borehole. As discussed by Ritter [36], selecting thicker insulation or a deeper borehole has considerable effect to the overall construction cost. We have used this method to determine the lowest investment cost for a building and to explore the optimal balance of active and passive systems by analyzing a simple 10x10 m² two-story brick building in Zurich with an opaque façade U-Value of 0.5 kWh/(mK) and with 20% glazing having a U-Value of 1.0 kWh/(m²K).

Results

Building Heating Operation

The standard heating operation is illustrated in Figure 5.7. The B35 pilot project will not have an annual heat demand less than 15 kWh/m² as stipulated by the stringent performance passive standards that focus on minimizing heat demand. Instead, an annual heat demand of 36 kWh/m² is predicted, but if the estimated minimum COP of 8 is achieved, the resulting annual exergy demand is only 8 kWh/m². This demonstrates how the performance of integrated low exergy systems can achieve high performance with active systems without the structural limitations incurred in passive house standards, as has been illustrated in previous work [12].
Figure 5.7: Operation of the system during the heating season. Capital labels correlate to lower-case labels in Figure 5.5 where applicable. The deep borehole (C) provides higher temperature base load heat to the heat pump (D), which can be supplied with a small amount of renewable energy (K) to produce low temperature heating (L) provided to the thermal mass (G) and decentralized air supply (H). The low temperature hot water storage (E) provides hot water that can be transferred through a heat exchanger (F). The shallow borehole (M) can be regenerated by cool temperatures captured by the PV/T panels (J).

In the heating mode, the heat pump is supplied by the deep borehole, Figure 5.7(C). For the B35 pilot in Zurich we expect temperatures around 15 °C. With these temperatures a temperature-lift of less than 20 K can be maintained, which will in turn guarantee a minimum COP of 8. In the heating mode, the small decentralized air systems Figure 5.7(H) must only condition the air to an acceptable temperature while the large surface-area radiant systems provides the sensible heating, thus reducing the exergy losses associated with using air as a heat transport medium.

During the heating season the hot water production becomes the critical limiter to the heat pump performance, Figure 5.7(E). There are a variety of means of operation that we have included to maintain a very low temperature-lift during hot water preparation. In the B35 pilot, the hot water is prepared at only 40 °C because this is the average usage temperature. It is a direct loss of exergy to store it at higher temperatures only for it to be mixed with cold water at the usage point. Higher temperatures that are infrequently needed are achieved with electric boosters as found in common dishwashers, and the 40°C heat is stored in a separate tank that heats incoming water directly through an efficient heat exchanger, minimizing the Legionella risk.

Another option for hot water supply is to exploit higher temperature anergy sources for hot water production, such as warm wastewater recovery and PV/T heat. Initially by simply capturing and briefly storing the warm wastewater or PV/T heat with temperatures usually greater than 30 °C a higher temperature is supplied to the heat pump. Such stochastic storage and capture has been modeled and optimized using exergy analysis [27]. Sunny periods will also achieve warm temperatures from the PV/T in the range of 35 °C, which can
be used as another supplement for hot water production. Finally, exhaust air has been shown to be a useful potential source for hot water production \[37\]. It should provide temperatures greater than 20 °C, which would provide a final backup to insure a temperature lift of less than 20 K.

During the heating season cold outside temperatures are encountered with cool nights and longer overcast periods. Under these circumstances the PV/T panels can be used to regenerate the shallow borehole by dissipating any excess heat that may have increased the temperature, Figure 5.7(J,M). The panels may also augment night cooling when clear night sky temperatures provide a radiation sink that can be used to dissipate heat directly following a warmer day. The different depths of the dual zone borehole not only provide optimal temperatures, but they also provide independent operation so that supply and regeneration do not have to be as carefully balanced as with many seasonal storage methods. This system facilitates the optimal extraction, storage, and utilization of the anergy sources.

**Building Cooling Operation**

During the cooling season, the system uses the building thermal mass to provide high-temperature cooling through the same supply system as for heating. Heat is removed from the building directly using the cool temperatures from the shallow borehole and can also be used to regenerate the deep warm borehole, as illustrated in Figure 5.8.

![Figure 5.8: Operation of the system during the cooling season. Labels again correlate to Figure 5.5 and Figure 5.7 where applicable. The shallow borehole (M) absorbs heat to provide direct cooling at around 10 °C (P) to the thermal mass (G) and decentralized air supply (H). The deep borehole (C) is regenerated by excess heat around 35 °C (O) absorbed by the PV/T panels (B), which can also be used by the heat pump (D) to generate average temperature hot water (E) with heat recovery (F). For the cooling mode, the shallow borehole will provide the average seasonal temperature of the region. This is usually in the range of 8 °C for Zurich, and for the 150 m deep borehole of the B35 project the temperature should be around 10 °C, Figure 5.8(M). At this](image-url)
temperature, direct cooling of the structure is possible, Figure 5.8(G). With the activated thermal mass, a surface temperature of 18°C provides high-temperature cooling to the space, while the 10°C temperature can be used to achieve some dehumidification if necessary. Again, the decentralized air supply does not participate in actively cooling the space, but rather on providing adequately comfortable temperature air upon entry to the space, Figure 5.8(H).

Most important to consider during the warmer weather of the cooling season is the regeneration of the deep borehole. The PV/T panels will easily provide adequate temperature heat for hot water during summer, and excess heat will be sent into the deep borehole to increase the temperature for the heating season as demonstrated by Figure 5.8(B,O,D,C). Not only that, but the heat extracted from the thermal mass can be used to regenerate the warmer deep borehole as well. Even what would be considered overheating from radiation can be seen as an anergy source. That excess radiation striking the floor behind a window, shown by Figure 5.8(G), can be captured with an appropriately designed hydronic system, thereby eliminating the potential of overheating and turning a potential source of exergy destruction in the building cooling system into an anergy store for the building heating system.

**PV/T Prototype Performance Results**

The reduction in demand facilitates the use of renewable supply, which is provided by the PV/T panels. This system is still under development in collaboration with various PV manufacturers. Currently, development is toward newly developed cells with efficiency in the range of 10-14%.

**Figure 5.9:** Thermal photograph of the experimental PV/T on the roof of the HPZ. The panel on the left has no heat removal and a surface temperature ranging from 50-65 °C. The panel with the heat exchanger active has a surface temperature that is reduced to below 35 °C and an increase in electrical efficiency of 25%. Laboratory results showed an increase of 12%.

Our experimental analysis on 1.66 m² PV/T panel showed a peak thermal performance of around 860 W (520 W/m²) and a peak electrical performance of 230 W (140 W/m²). This is a thermal efficiency of around 50% and an electrical efficiency of 14%. What is most
interesting is that the cooling effect of the heat extracted for the heat pump had the added benefit of increasing the panel electrical efficiency by 25%. The cooling of the panel is shown in the thermal photograph in Figure 5.9.

The laboratory tests of 1.58 m² test panel with simulated wind showed that the thermal performance with a control input of 800W/m² had an overall thermal efficiency with no wind of 0.54 with no electrical load, and an efficiency of 0.47 with electricity. With wind the panel had a thermal efficiency of 0.42 without load and 0.37 with load. The electrical efficiency was 12% when fully cooled, which was an increase of 13% over the panel that was not cooled, supporting the results we found in our own experimental setups.

The potential multiplication of the electricity output from the PV cells using a heat pump increases the performance far beyond what is possible with solar thermal units alone. With a COP of 8 and a PV efficiency of 12%, 96% of the irradiation is transformed into heat supply, and if electrical efficiency is improved or a COP greater than 10 is achieved, as has been already been shown experimentally [22], then more than 100% of the solar input is transferred to heating. Performance greater than 100% is of course dependent on heat supply from good anergy sources like the dual zone borehole. With our system for example, a temperature lift of 10 K for PV/T supply to hot water production as shown in Figure 5.8 should accomplish a COP of about 15 according to Figure 5.4.

Building Simulations

Previous work compared the PV/T system operation on a version of the HPZ with a dual zone borehole and one with a standard borehole, which demonstrated the advantage of being able to regenerate the deep boreholes while simultaneously using the shallow boreholes for cooling [38]. Here we compare directly a non-LowEx version with additional insulation and no PV/T versus a LowEx version with PV/T and the dual zone borehole. The comparison allows us to analyze the potential benefits of the renovation decisions made at the HPZ and the new technologies being implemented at the B35 pilot project.

Our simulation of the LowEx and non-LowEx renovation showed the benefit of adding insulation, but also how the active systems can greatly reduce the exergy needed to meet that demand. The improved façade of the non-LowEx model reduced the annual heating load to 31 kWh per m² of usable floor area whereas in the LowEx model’s old facade still demands 50 kWh/m². During the cooling season the LowEx model has a lower cooling load of 44 kWh/m², than the non-LowEx with 47 kWh/m² because the added insulation reduces the possibility of natural nighttime cooling. Due to the deeper boreholes 5% more anergy can be extracted from the ground in the LE model. Most importantly, the improved anergy source for the LowEx model leads to an annual heat pump COP of 7.9 instead of 6.9 for the non-LowEx. Therefore, even with the higher heat demand, the added benefits of the PV/T heat and improved dual zone borehole anergy source, the required electrical exergy demand for the HP is 7.6% less for the LowEx model.

We must also consider the auxiliary power of for the LowEx systems. The boreholes were simulated with the same flow rate and the same pipe diameter and similar total length. We modeled the pressure drop over a range of pumping scenarios, which verified that the pumping costs for the boreholes in the two models can be assumed to offset each other. Therefore, the additional pumping cost of the LowEx model is represented by PV/T installation. For the 450 m² system, and for 3200 hr of operation, the energy demand was only 1 kWh/m² assuming 20% efficient pumps, which is small compared to the heating and cooling demands.
For the hot water production that is not considered for the office building, there is a large savings potential from the simple change in the storage temperature. If it can be supplied at a lower average temperature while also finding higher anergy source temperatures for the heat pump, the temperature lift can be reduced to a range between 10 and 25 K. As shown in previous work [27], this could improve the heat pump COP range of operation from 2-4 to 6-15, bringing the exergy input needed down dramatically compared to natural gas or electric resistance heaters. Instead of 2400 kWh, less than 410 kWh are needed for each person’s annual hot water needs [27].

Cost Considerations

In general, the low exergy system design creates a way to separate the various heating and cooling demands from the actual input needed to create them. By optimizing the anergy source temperature and using exergy analysis on the supply system, a new method arises to limit the primary energy demand without needing excessive limits on heat losses [11]. We can achieve very high performance with walls that are not extremely thick. The B35 project has rather good thermal performance at 36 kWh/(m²·yr) for heating, which meets the Swiss energy saving standard Minergie, yet it does not make sense to try to reach the stricter passive house or Minergie P standard. Instead, with walls that are less than 35 cm thick, a primary energy demand is achieved that can easily be met with renewable energy supply. Furthermore, due to declining cost for electricity from renewable sources, investing in active building components can actually reduce the operational cost of a building compared to the cost savings achieved by maximizing the thermal performance of the façade.

Our analysis of investment cost demonstrates the benefits of finding a balance between active and passive building components. As discussed by Ritter [36], the overall construction costs for active and passive systems depend considerably on the specific costs, which vary from site to site and from building to building. One optimal balance cannot be generalized for all buildings, but can be easily considered for individual cases. The results of Ritter [36] show that when comparing strategies for building operation with the same operational costs, the option with the lowest investment is not necessarily the option that achieves the lowest passive heating demand. The common practice for renovation projects is maximizing the thermal resistance of the façade first before improving the building system.

In our simple building analysis we have found when the investment breakdown for a borehole and insulation is 87.5% for the insulation, The Swiss Minergie Standard of 38 kWh/m² of annual heating demand is met. But in order to actually minimize the investment, the insulation should only have a 72% share and the borehole, 28%, more than double what is suggested by the heat demand based standard. Therefore the investment of active and passive system components is not necessarily optimally balanced when using only heat demand limits.

The borehole system is typically the primary cost of the active systems. Thus, the collective use of boreholes considerably reduces the costs per building and shifts the balance of investment toward active components. Additionally, less dependency on passive components creates a higher flexibility in the design of the structure and also reduces the material demand. Finally, the reduction of the usable space caused by excess insulation are an important financial and design aspect in cities of high density.
Conclusions

We have shown the great potential for the implementations of a variety of low exergy systems. Results of these design practices have been presented in the form of various technologies. These technologies are being implemented in integrated systems that minimize the temperature-lift of a high-COP heat pump. We have shown why the performance of such an integrated system is expected to be very high. It provides an alternative perspective from passive house designs by eliminating the design restriction resulting from heat demand oriented system optimization. The active system creates a wider range of design possibilities by supplying heat demand while independently minimizing exergy input.

The concept of low exergy building systems is being extensively implemented in the B35 project in Zurich, which demonstrates how systems are implemented. The PV/T panels have been experimentally analyzed, showing a thermal performance of about 40% and an electrical performance of 12-14% that has been increased due to the cooling provided by the thermal system. An installation of the HPZ renovation was simulated, which reveals a 7.6% performance increase when installing a PV/T system and a dual zone borehole instead of 10 cm of additional insulation and a standard borehole. Finally, a cost analysis demonstrates the importance of considering investments not just in passive systems, but in active systems such as boreholes as well.

We have presented many low exergy systems at various stages of development and implementation. The principle component is the heat pump. The lack of a market for very low temperature-lift heat pumps in the building sector is a major obstacle. Nevertheless, there is no reason why these machines are not thermodynamically feasible. The collaboration between the ETH Zurich and HSLU Horw will hopefully lead to a more rapid development in this field with the first prototype heat pump due in 2011. The B35 project and the HPZ renovation will also be completed by 2011, and the new HIB building will be built in 2012. Testing and results from these LowEx projects will produce further validation of the technologies described while being positioned at the forefront of new technology creation and implementation.

Development of low exergy building systems will broaden the palette of tools available to building architects and engineers to create buildings that have low energy and exergy demand. The resulting new systems and methods will lead to building construction and operation that generates a minimal amount of CO₂ emissions, and will move us down the path toward zero emissions for the building sector.

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6 Reduce CO2 to Zero Emissions

6.1 Overview and Reference

This paper is a result of an international collaboration of building system and researchers and designers that analyzes a wide variety of advances that are possible in the building sector, including low exergy concepts, that can help move toward zero emissions.

Paper:

Sustainable Cities and Society
Forrest Meggers, Hansjürg Leibundgut, Sheila Kennedy, Menghao Qin, Mike Schlaich, Werner Sobek, Masanori Shukuya. “Reduce CO2 from Buildings with Technology to Zero Emissions.” Submitted to Sustainable Cities and Society 2 (1), February 2012, 29-36
6.2 Context of Paper

Besides the operation within a single building, another important consideration in this research is how these ideas can play a role in the even broader context of greenhouse gas emissions and climate change. As part of a very diverse international collaboration in preparation for the 2010 Holcim Forum for Sustainable Construction a paper was developed discussing the potential of the building sector to reduce its CO2 emissions. It has been submitted as, “Reduce CO2 from Buildings with Technology to Zero Emissions,” to the journal *Environmental Science and Technology* as a policy analysis, which focuses on the technological and methodological aspects of building design, construction and operation.

This describes the largest potential implication of this research on exergy analysis of buildings. It also frames the concept within a more globally understood problem. This emphasizes the relevance of the developments that are made in the building sector, and the potential impact of the technological leaps in performance that can be demonstrated by integrating low exergy systems in buildings. At the same time is helps place these impacts in an analysis of the changes that need to take place across the entire sector and beyond just the exergy consumption of the buildings, but also the indirect impacts of material and construction decisions.

The international group of experts that were leveraged to generate this paper provides a large pool of knowledge in these other areas. More interestingly, it is in the overlaps between these areas of knowledge, and specifically with reference to this research on exergy, where mutual and compounding benefits are uncovered such as reduced material through better active system design, and decreased exergy consumption through use of new construction materials. Although this paper does not present new original research findings, it is very relevant to the research that has been done, and provides a significant context for future developments and shows the implications for low exergy systems as a central contribution to the reduction in CO2 emissions from the building sector.
Paper 6.1: Reduce CO2 from buildings with technology to zero emissions

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Abstract

This paper represents a unique collaboration between experts in architecture and engineering from around the globe to evaluate the true potential to reduce CO2 emissions from buildings. The result of this experiment in remote collaboration between Europe, USA, Japan and China, was a summary that was generated for the Holcim Forum workshop, “Reduce CO2 – With technology to zero emissions.” This covers challenges of reducing emissions from building construction, operation and maintenance while also presenting an array of potential solutions. Here we expand on that work for the benefit of a broader audience.

The paper covers the overall problem of building emissions, both direct and indirect. It discusses the often-overlooked impacts of building material use. It also reviews the problems related directly to building CO2 emissions and energy consumption, as well as new analysis methods for better system design. Finally, many new processes are discussed that have the potential to drastically reduce building CO2 production to nearly zero. In summary we encourage new perspectives that increase the utilization of new methods and systems, thereby providing examples of technological groundwork that can incite new policy to reduce building CO2 emissions.
1. Introduction

In 2010 a group of experts were virtually assembled from around the world to address the rapidly growing problem of CO2 emissions from the building sector. In this paper we present the results of this multidisciplinary cooperation between designers, architects and engineers from Europe, USA, Japan and China. The project grew from this team, who led the “Reduce CO2 – With technology to zero emissions” workshop at the Holcim Forum in Mexico City.

We present our findings in a set of focus areas that guided our concurrent intercontinental work, giving the paper a nontraditional structure. First, we address the (1) Overall Problem of buildings and their current impact on the environment. Then we consider more in depth the (2) Material Problem and the (3) CO2 Problem of buildings. Next we discuss a sample set of (4) Analysis Methods and then (5) New Processes that the team of experts compiled to address the problems previously described. In conclusion, we consider the potential (6) Impact of Solutions that have been discussed in the form of design and analysis methods as well as the innovative new technological options.

2. Overall problem

Contemporary building has inherited the assumptions and practice models of Modernism, methods of thinking and practice that were developed in the last century, and are based upon historic cultural conditions of the 1940s, 1950s and 1960s. These inherited, and largely unquestioned assumptions of Modernism present us with a large problem when it comes to their construction, maintenance and operation. At best they cater to a fundamental need in the form of shelter, and as a highly capitalized industry, their construction responds to prevailing market forces. But insofar as we have extended their functionality and complexity to provide modern comforts, they are now the largest single contributor to global CO2 emissions. When all aspects of buildings are considered, some estimate that over half of emissions are related to the building sector (E Mazria, 2007).

This is due to a variety of factors. Buildings use 35% of energy in the world and are directly responsible for 35% of global emissions. Two-thirds of global electricity production is for building operations. When including construction and maintenance, it becomes clear that 50 – 60% of global resources are consumed by buildings while also causing more than 50% of global waste production (Roodman & Lenssen, 1995).

The range of direct and indirect impacts that buildings have on the environment makes it easy to overlook the full impact of buildings as an individual sector. The impacts are often grouped into other sectors even when their creation is actually a result of building construction, maintenance, or operation. This is illustrated in Figure 6.1 as reported by the IPCC (Mayer, 1999; Nabuurs et al., 2007; Rogner et al., 2007), where the true impact of the building sector is masked by the Energy Supply, Industry, and Forestry sector, all of which are heavily influenced by construction and operation of buildings.

Reducing the CO2 production of the building sector along with these other negative impacts is a challenge that must be met quickly and decisively. Luckily there are many technical solutions that already exist (Hoffert et al., 2002), and experts all over the world are implementing new strategies that will lead the way in changing how we produce and provide a modern built environment (Meggers, Ritter, Goffin, Baetschmann, & Leibundgut, 2011). This includes finding new materials and methods to address the sometimes
overlooked CO2 produced directly in building construction while maintaining focus on reducing the massive amounts produced from building operation.

One important strategy involves changing the perspective people have on building materials. Every component of a building has an associated energy use and CO2 emission inherent in its extraction, production, and transport. This “grey energy” and the resulting “grey emissions” of materials are usually overlooked, and even when it is addressed, the data is not usually readily available. This aspect of building materials must be considered in every design if we are going to address the full effect of buildings on CO2 emissions and pollution (Vieira & Horvath, 2008).

Figure 6.1: Fraction of global emissions attributed to buildings. Often only the direct influence of residential and commercial buildings is considered as shown (a) in the data provided by the IPCC (Rogner et al., 2007). By considering the description of the IPCC (Levine et al., 2011; Nabuurs et al., 2007), estimates can easily be made of the sectors that are partially results of building sector demand (b), which demonstrates the potentially large overall impact in the range of 50% (c).

Energy use from building operation is already often addressed as it causes the most significant and obvious impact, but there is still much more that we can do. There are many ways to integrate energy saving systems into buildings, and there are better analysis methods to improve building design. We can look beyond simple energy balances and resource consumption, and evaluate their direct and indirect impacts based on their quantity and quality using concepts from the first and second laws of thermodynamics. The industrial revolution brought the ability to control and condition buildings, and this was achieved with the new widespread availability of high value energy sources. Now the consequences of wasting those sources are clear, and we can use these new concepts and ideas like exergy and anergy to exploit the potential of lower quality renewable sources (Meggers & Leibundgut, 2011).

There is a vast potential in the integration of solar energy into the supply of energy to buildings, both in centralized large-scale plants (Mills, 2004; J Schlaich, 1995) as well as in smaller decentralized systems directly integrated into buildings (Kennedy, 2011). When it...
comes to finding a sustainable energy supply for buildings, one can already recognize that there is more than enough solar energy available. All that is missing is a feasible method to capture it and supply it to buildings, which is influenced by a variety of factors from research and development to political will. Therefore, it remains important to consider all potential renewable energy sources, because the best solution will always depend on the available technology and its applicability in different locations and situations.

It is one of our main tasks to put forward a selection of the most practical and impactful energy solutions and an idea of how industry could get there from where we are today. The matter of climate change is not an issue for academic and/or political circles alone, and it is our responsibility as a team of architects, engineers and “experts” to put a solution mix forward. It needs to be a solution mix to address the political and industrial realities. We are not going to have a single source of power or a single industry that is going to solve the problem. Different parts of the world will be able to bring different resources to bear, and all must be part of the overall response.

Finally, a fundamental part of the overall problem is the building user. The decisions made by users vary widely based on culture and lifestyle around the world. It is important to make the usability of buildings one that also encourages not just best practices in system operation, but also in user operation. Intelligent systems can help minimize inefficiencies in operation, but more advances in human factors and understanding the best way to provide and maintain a comfortable environment for all users must be included in all new advances to bring building CO2 emissions to zero. Central to this is the building construction industry. In order for users and building owners to make these decisions, they must have choices, and this means that the construction industry must re-align its products and processes, prioritizing the efficient use of energy in the manufacture, shipping and erection, and deconstruction of buildings.

3. Material problem

The material problem for buildings takes many forms. As mentioned, the grey energy and emissions must be considered, and the production of building materials requires the use of more high value energy and resources as compared to building operations. There are also environmental problems with the byproducts of material used in buildings, and there are limitations on the extraction of resources used for various building components. One must also consider the infrastructure used to support the built environment. There are many technological advances that must be implemented to solve the problems of resource depletion, corrosion, pollution, durability, lifespan, etc. associated with building materials.

First of all, new construction should be built more sustainably such that it not only minimizes negative aspects of construction and operations, but that it first maximizes building lifespan, which can be done by removing design aspects that will be rapidly outdated. Also all necessary components with limited lifespans should be designed for reuse or raw-material-recovery. This must be achieved in all aspects by thoroughly breaking down the complexity of the building into its parts, and understanding any trade-offs between integrated systems so that a wholly sustainable solution can be achieved.

This can be facilitated by an awareness of the rapidly expanding array of materials available for structures, enclosures and systems. The past century has seen an explosion of development in material science. This is not just the development of new materials, but also the discovery of many new uses for existing materials. Concrete has been redesigned and reformulated through thousands of iterations and is now three times stronger (Fernandez,
Also new formulations can incorporate waste streams that would otherwise go to landfills and also reduce the significant CO₂ emissions from the concrete industry (Huntzinger & Eatmon, 2009). Insulation has improved between 1.5 and 3 fold from standard mineral wool, and new materials are entering the building market like Aerogel designed for the aerospace industry with performance 3.5 times standard insulation (Fernandez, 2007; Fesmire, 2006). Besides these improvements, new possibilities for integrating sensors and active components into building materials are available. This includes the incorporation of photovoltaics into building fabric and the ability to actively monitor and optimize the use of heating, cooling, lighting and ventilation using components integrated into the building structure (Fernandez, 2007; Kennedy, 2011). Simply being conscious of the array of material options with better performance will encourage stakeholders from architects to builders to owners to reduce both grey and operational CO₂ emissions.

Along with being aware of the material options, overconsumption of building materials must also be considered. There is extensive use of steel in large construction projects now without consideration for the large energy requirements for its production. Another principle building component that is also overused is concrete, with massive structures being built that could be achieved with a more 'lightweight' design. Additionally, the use of limited resources such as copper and others must be done such that they are recovered and not lost in waste streams. This requires an understanding of the concept of industrial ecology and how it can be applied to building material flows. We must consider the indirect and direct impacts of materials with sensitive resource demands or environmental impacts, and also contemplate in design the number of people using various aspects of the structure so that the material selection (kg/person not just kg/m²) is reasonable.

There is a great potential in the field of lightweight building design. This minimizes the consumption of raw material for buildings. A typical residence in Germany contains enough grey energy in the materials to operate the building for 25 years. The amount of materials that need a high quantity of fossil energy to be produced has to be reduced. Lightweight materials do not simply imply low density, but rather a high ratio of strength/density or stiffness/density. These materials must be favored. Lightweight structural and lightweight nonstructural systems must also be favored. This density optimization accompanied by intelligent integration allows the materials to be more easily maintained and recycled; a more simplified construction can be applied using simple concepts like hook and loop fasteners, magnets, and quick fasteners, which facilitates deconstruction and separation of materials for reuse (Sobek, 2011).

One technological advance in lightweight structures is concrete with expanded aggregates pictured in Figure 6.2. This concrete is generated with a foam-like structure such that the thermal performance is greatly improved, and the required mass per cubic meter is reduced. So-called infra-lightweight concrete with a strength of 8 MPa can be used as a structural component of small buildings yielding U-values of around 0.3 W/m²K for a 50cm thick wall (M Schlaich & Zareef, 2008). This allows again for fair-faced concrete architecture without additional insulation. Having only one load-bearing and insulating building material can greatly simplify construction, reduce material demand and improve building energy efficiency, all at the same time. However we must remain aware that the use of concrete at all, also poses significant problems in terms of it dismantling.
Figure 6.2: An example of expanded concrete with lighter weight and better thermal resistance, which reduces material demand.

In general, for an entire building, the impact of the grey emissions in the materials should be kept below 0.5 kg per square meter of floor area and year of lifespan. Lightweight materials will help to achieve this, but they must be considered holistically. It is likely that tactility, mass, and haptic materiality will come to the fore (Kennedy, 2011).

Finally, when it comes to the end of life of a building, there should be careful consideration for the processing of the materials. This should be considered already during the design phase of any building, where composites that are difficult to deal with are minimized. Materials should be used that can be directly reused without having to remanufacture them. If they cannot be directly reused, they can be recovered as raw materials. If they must be recycled, they should be utilized at the same level of quality, thereby eliminating any downcycling or waste. For example, a Chilean copper mine contains 100 units of copper per ton of material extracted, and a modern building contains 40 units per ton of material. Yet this rather abundant source of valuable material is rarely utilized due to its embedded nature in the construction and the difficulty of removal during standard methods of deconstruction, otherwise known as demolition. With more intelligent incorporation of these valuable resources in designs, and with construction that actually facilitates an efficient deconstruction, significant strides can be made in reducing the impact of the building sector (Sobek, 2011; Vieira & Horvath, 2008).

4. CO2 problem

The problem of CO2 emissions is at the core of the necessary changes in the building sector. We agree that the anthropogenic emissions of greenhouse gases are a threat to the future prosperity of our entire race, and the large potential reduction in our sector of buildings must be addressed rapidly and extensively. The extensive compilation of research from thousands of scientists around the world done by the IPCC has demonstrated the importance of limiting the potential anthropogenic temperature rise, and after much negotiation, the international community agreed with the Copenhagen Accord that temperature rise should not exceed two degrees (Ramanathan & Xu, n.d.). Out of any single sector, we have one of the largest opportunities to impact CO2 emissions.
We are presenting ideas to transform the building sector to stop the growing emissions of CO2. We are not fixing a specific target and schedule of reductions. We are saying that it is possible to have buildings with very near zero CO2 emissions from both construction and operation, and we hope only to “feed that scientific advice into policy” (Schenkel, 2010) with real information about technologies that provide this potential. We can generate and implement the designs and technologies needed to meet this target. Emissions caused by energy use can be directly reduced by changing the source and by making buildings more efficient. As discussed, the grey emissions of materials must also be evaluated and reduced. There are large amounts of emissions from cement production for concrete and there are already new technologies available to reduce this source (Huntzinger & Eatmon, 2009; M Schlaich & Zareef, 2008).

The largest portion of CO2 emissions from buildings remains in their operation, which results in the fact that buildings demand 2/3 of electricity generated (Roodman & Lenssen, 1995). But one added benefit of this fact is that CO2 emissions of buildings are reduced by improvements in the electricity production. As described, this can be done in building projects through integrated systems, but the technology for renewable energy generation and supply is also growing. It has been shown how coal, the most CO2 intense electricity supply, could be phased out of the US in the next 2 – 3 decades (Kharecha, Kutscher, Hansen, & Mazria, 2010). Globally, a path has been demonstrated for the implementation of technology that would lead to climate stability (Hoffert et al., 2002). In terms of buildings compared to other sectors like transportation, it was recently demonstrated that it would be more effective to use the biomass being used to create transportation fuel instead as fuel for electricity production (Campbell, Lobell, & Field, 2009).

The question is only how quickly can we implement, and generate the paradigm shifts necessary in the building sector to reach the large potential impact that is surely within our reach. Zero carbon emission buildings will have to be the standard in the future. It is up to us to make that future feasible with our ingenuity and creativity. As we describe, many of the technologies for buildings are already available. It is only the implementation and scaling up of that is needed to meet many of our goals. The change in culture that is required to do this can be seeded in the education of architects, engineers and constructors, as well as by governments and business leaders in the respective fields.

5. Analysis Methods

We have discussed the need to address grey emissions and the full influence of buildings on CO2 emissions. All of the changes needed are going to require not only new perspectives, but also new methods of analyzing and evaluating the impacts of buildings.

These new methods include better systems to model and predict building performance as well as new design techniques for building systems and technologies. In many cases designers remain unaware of the CO2 emissions that will result from a building they are creating. Illustrations like the zero emission chart shown in Figure 3 make it easy to see how the exergy demand per m2 of building combined with the CO2 intensity of that supplied exergy can be plotted to demonstrate the actual emission intensity and thus sustainability of the building. Every building should have its performance evaluated, and tools need to be made available such that this process is possible for the wide range of people working in the industry. This includes more tools for energy and emission modeling, especially in the early design phases, as well as better access to tools that help evaluate material life cycles (Schlueter & Thesseling, 2009; Sobek, 2011).
Reduce CO2 from buildings with technology to zero emissions

Figure 6.3: NS-E diagram or Zero Emission Chart separating the non-sustainable (NS) level of exergy supply CO2 intensity and the actual net delivered exergy (E) of the building, allowing the designer to consider efficiency and supply improvements individually to move the building operation toward zero emissions. As designs increase building performance, the point moves to the left, which eventually facilitates the integration of more renewable energy in design steps, which in turn moves the point down and toward zero emissions at the x-axis.

There are also further scientific methods that can help improve building analysis. Currently any analysis of a proposed building design is done using simple energy balances based on the first law of thermodynamics where energy supplied to a building is matched to the energy demanded by heat losses, ventilation, lighting, etc. This rather simple methodology helps minimize the amount of energy used by a building, but by applying concepts from the second law of thermodynamics the optimization can be extended to also evaluate the quality of the energy source being consumed (Meggers et al., 2011; Torio, Angelotti, & Schmidt, 2009).

This extension of analysis can be achieved with the concept of exergy, whereby both the quantity and the quality of energy are defined. Exergy exposes the difference between two equivalent amounts of energy at different temperatures. A higher temperature source has more value. In the case of buildings, the room air is only at a moderate temperature compared to temperatures for hot water or to the extreme temperatures found in combustion processes. Using exergy analysis we can better match sources of energy that are also not of excess quality. This demonstrates the wastefulness in many building systems that use combustion to generate very high quality energy to provide low quality heat to a room. The loss of quality is only exposed through exergy analysis. Because fossil fuels are the primary source of CO2 emissions, exergy analysis directs any necessary use of their high quality combustion only to areas where that quality is actually demanded and utilized.

We can also use the second law of thermodynamics to improve on integrated heat pump systems and maximize the use of other low value energy sources, or “anergy sources,” from the environment or from thermally valuable waste streams. The concept of anergy, which is theoretically defined as dispersed energy, can be used to label these resources freely available around a building as potential anergy sources. They become a consideration in the overall building design, and with exergy analysis improve building performance. The
performance of a heat pump is directly related to the temperature of the heat source from which it is pumping heat. By evaluating the potential energy sources on a building site based on their available temperatures and the second law of thermodynamics, heat pumps capable of moving more than seven units of heat per unit of electricity are easily achieved (COP>7) with proper low-temperature-lift design (Meggers et al., 2011). By recognizing the potential of low-temperature-lift heat pumps, solar hot water generation becomes obsolete. With a PV panel at 20% efficiency connected to a heat pump with a COP>5 will already provide heat equal or greater than 100% of the incoming solar energy.

The natural exergy available in our immediate environment should be harnessed and smartly consumed so that we can provide a basic need. A simple solar water heating is similar to having well insulated building walls for reducing the space heating load, which is similar to having external shading devices for reducing the space cooling load, which is similar to making use of daylight available nearby window room space for reducing the space lighting load, and so on. Exergy analysis provides a further scientific tool to validate the benefits of better building designs. Recent exergy research focusing on the built environment together with occupants’ thermal comfort and well being has revealed the right track leading to sustainable solutions, namely the low-exergy system solution for heating, cooling, lighting, ventilating, etc (Shukuya, 2009; Simone et al., 2011).

6. New processes

There are many new processes that will play a key role in reducing CO2 emissions to zero for buildings. Much of their development will be the result of thinking outside the box. For example, by considering the new analysis techniques based on exergy, new ideas on how to better process cement can be considered. Is it better to utilize the high value of renewable wood combustion for the high temperatures needed to make cement, instead of transporting and distributing that wood for combustion in houses that need only moderate room temperatures? Or is it better to limit the use of cement, and favor lightweight renewable wood or wood by-products as a construction material that can also sequester carbon, and can be easily de-constructed and re-cycled? These are the types of questions that must be answered.

Yet, there are many new processes that have been extensively studied. In the realm of energy production, there are hundreds of ideas for new renewable systems (Hoffert et al., 2002). The solar updraft tower is a large circular glass greenhouse with a high concrete chimney in its center. The air under the roof is heated by the sun and moves up the chimney. The artificial wind thus moves turbines that in turn produce electricity. Unlike other solar thermal power plants no cooling water is needed and the plant works also with diffuse solar radiation. Simple heat storage allows for 24h energy production. All this while high-productivity agriculture is stimulated under the system. This way CO2-free energy can be produced at a large scale and much cheaper than with photovoltaic panels. However, large initial investment for this unique renewable energy production method is needed to build the first large-scale plant, and this has not happened yet. The time needed for the solar updraft tower to reproduce the overall grey energy that was invested into it is 2.5 years. This is not much, especially if you consider that the life expectancy of such a tower is at least 100 years. Regarding the cost of electricity it produces, the estimate is 8 – 10 Eurocent/kWh (Jörg Schlaich, Bergermann, Schiel, & Weinrebe, 2004). The solar updraft tower is an example of one potentially revolutionary concept that, if successful, could eventually provide large amounts of renewable energy at the scale of modern power plants.
There are also many advancements in other solar processes, including dropping prices of photovoltaic production and new concepts for large scale solar-thermal power plants that could provide electricity production 24 hours a day using thermal storage during dark hours (Mills, 2004). Additionally, there is a still huge potential for expansion in wind energy and other renewable sources that are being researched such as tidal and geothermal sources (Kharecha et al., 2010).

Another way that buildings can impact the success of renewable technologies, specifically solar, is through integrated systems. If solar collectors are integrated into the structure of a building, they can play dual roles while having still one cost (Kennedy, 2011). By having renewable energy generators like solar panels considered in the architectural phase of design, they are also less likely to be value-engineered out of the project and are not seen as simply an add-on. Furthermore, the trend of placing PV on roofs generates further obstacles because it is a reengineering process. The high temperatures on the roof reduce efficiency of panels as well. But by considering this problem in terms of the whole building system, the resulting medium temperature heat actually has value that can be extracted. Integrating a heat exchanger and cooling fluid can increase panel efficiency and capture another portion of the sun’s energy as heat. These new hybrid photovoltaic thermal (PVT) panels shown in Figure 4 could capture solar energy using inexpensive PV technology combined with simple heat exchangers, generating a better combined-efficiency than much more expensive high-tech PV panels and vacuum-tube solar-thermal panels (Meggers et al., 2011).

**Figure 6.4:** Hybrid PV panel with inexpensive low-grade heat extraction attached to the rear for usage with heat pump systems.

Not only should we consider the new technology driving the improved processes for the building sector, but we should also consider the new processes that are being discovered from existing systems. A simple system for an advanced self-cleaning building coating has been shown to reduce local air pollution around the structure through chemical reactions (Fernandez, 2007).

Technology transfer from existing industrial manufacturing to construction can also be considered. This includes computer driven cutting equipment, which can make use of flat sheet products very efficiently with optimization software. The accretive construction processes found in nature can also be studied fruitfully both as a source of inspiration and for creating solutions. The use of high throughput manufacturing processes that consume less energy will need to be emphasized. Flexible thin-film solar technologies offer the potentials for new energy harvesting building products with inexpensive roll-to-roll and deposition production processes and very low carbon manufacturing footprints. The average greenhouse gas emissions from thin-film PV production (40g CO2/kWh) are less
than half that of that of equivalent-power silicon panels, and less than 5% of the emissions of petroleum, coal or natural gas energy sources (Fthenakis, Kim, & Alsema, 2008).

However, the inverters for converting DC supply to AC for consumption in the building are also inefficient. We must consider better ways to integrate generation systems while also recognizing the potential of DC power supply in buildings. Most electronics today consume DC power already and AC supply is a relic of large centralized power generation and distribution. Much more efficient decentralized systems can be realized if DC current can be used directly. Also, as stated previously, by integrating heat pump systems with PV, very effective methods of generating heat from solar energy can be achieved. The overheating problem on the roof can be turned into a solution by capturing that heat to further improve heat pump performance, while at the same time cooling the panels to increase their efficiency. This smart interdisciplinary planning of integrated systems needs to become a standard part of the design process (Sobek, 2011).

In fact, there should be a new organization of the planning process itself. This will allow better consideration of the new important aspects of design coming from energy use, emissions, and material use. This includes the use of new procedures that incorporate life cycle analysis including better end-of-life planning (Vieira & Horvath, 2008). Planning the EOL (end of life) scenario includes easy disassembly or dismantling of the building as well as of its parts and, of course, all questions related to the question of what to do with the leftovers (Sobek, 2011). This leads to a better consideration of the material problems we have discussed. We need, parallel to the reduction of fossil energy use, to consider the embedded grey emissions, cleaning, repair, modernization and EOL aspects in the design process. If we do so, a new improved planning process will evolve to be much more interdisciplinary and much more intricate.

The process of developing high performance buildings themselves can be re-evaluated as well. Currently the trend is to insulate a building to the extreme and to, at the same time, reduce the rate of air exchange to minimize losses. This technique is based on using passive methods to fight against heat loss rates and ventilation losses. In the most extreme case of a “passive-house” standard, a large enough barrier to outside conditions is built such that just the internal gains of the building can provide adequate heating. Nevertheless, this creates a large disconnect from the environment. The application of passive-house technology is architecturally critical if applied to buildings that already exist and extremely critical if applied to historical buildings with historical facades. The thick multi-layers used as insulation and exterior plaster must be viewed critically under recyclability aspects (they are, typically, “toxic” or “special waste”) (Sobek, 2011). Also, if one considers the added benefit of the final 10 cm of a passive-house wall (often >50cm), the added benefit of those final centimeters is equivalent to just the first half-centimeter of insulation as illustrated in (Meggers, Mast, & Leibundgut, 2010) and shown in Figure 5. This is due to the diminishing returns of excessive insulation. Even more importantly, we should not focus on creating a thick barrier to the outside climate, because different buildings need solutions aware of and adapted to their different climates. Solutions like passive house designs that might be effective in some temperate climates can be inflexible and problematic in hot and humid climates.
Figure 6.5: Change in building performance with excessive insulation. The last 10 cm only improve the performance by an amount roughly equal to the first 0.5 cm.

We propose the calibrated combination of passive and active systems. The integration of more active systems like the integrated solar and high performance heat pumps can allow a more flexible operation that does not fight against environmental conditions, but instead maximizes the exploitation of environmental conditions to increase performance. This design process generates an “active-house” that can more easily adapt and maintain comfort, while requiring less material and being more easily designed for EOL. This also naturally allows for a more simple integration of new energy generation paradigms using PV and other renewable sources.

Along with these new renewable sources comes the storage that many would require to surpass the obstacles created by their stochastic nature. Buildings have the potential to play an important role in this storage system, and in addressing this stochastic nature of renewable power generation, because buildings can be designed to better match this stochastic aspect of supply. In doing so the storage helps generate a constant stable renewable supply that allows buildings to help even the electricity demand that currently peaks heavily during the day.

Buildings are also surrounded by potential stores of low-value energy. Just as we can address high-value energy with the concept of exergy, namely not-yet dispersed energy, to allow us to compare various anergy sources; we can also address the potential utilization of these low-value sources that are not yet dispersed in the environment around a building. We can evaluate how some amount of exergy can be consumed and stored smartly for heating and cooling. This is achieved by shifting heat spatially from the ground or the surrounding to a more valuable point (i.e. ground source heat pumps), and/or by shifting heat temporally from seasonal or daily points in time to a different point where it is more valuable (i.e. seasonal heat storage or night cooling). For example, on the one hand, during winter seasons, thermal energy under the ground can be evaluated to have some “warmth”, namely some amount of “warm” exergy, so that this exergy can be exploited by a heat pump from the ground below. On the other hand, during summer seasons, thermal energy under the ground may be evaluated to have some “coolness”, namely some amount of “cool” exergy, so that this exergy can be exploited for space cooling.
Similar ideas may be applied and realized by a smart design of building envelopes with an appropriate implementation of heat capacity and insulating characteristics of materials. Storage systems are being rapidly developed and range from short-term storage using phase change materials (PCM) to long-term storage multi-zone geothermal boreholes. This, along with continuing advances in electricity storage using batteries and fuel cell, show how technologies can create a more stable sustainable power supply to, and consumption by, the building sector.

7. Impact of solutions

The goal of our solutions for the field of building design and construction is to reduce the subsequent anthropogenic CO2 emissions to zero. These are a result of direct emissions in construction, indirect emissions from material usage and from energy use during operation. Any direct emission from combustion in buildings generates a large destruction of exergy and should be avoided. We have presented a variety of aspects of this challenge along with potential solutions, both physical and systematic.

Material usage in buildings must include consideration for the grey emissions of the material. Life cycle analysis (LCA) and end of life (EOL) planning have to become a standard part of material selection if we are to successfully reduce the indirect impacts of material consumption for buildings, especially considering that buildings currently generate over half of global waste. This change in consideration for materials can have a significant impact on CO2 emission reduction that would otherwise be overlooked.

The CO2 emissions from buildings must also be evaluated as a standard part of the design process. We must use our technological advances and best available practices to rapidly change the current situation where buildings are the largest single sector generating CO2 emissions. The solutions are available. We must only demonstrate their feasibility and expand their application. This will generate a great stride toward negating emissions from buildings.

In order to be successful we must consider analysis methods that account better for the way energy and materials are used in buildings. High value energy sources can be more effectively utilized by applying concepts of exergy analysis to match the supply quality with the quality actually demanded by the building systems. With the new analysis methods comes the essential simplification of modeling tools that make performance analysis available to all stakeholders in the building process. This includes all aspects from energy to life cycle analysis of materials.

Finally, we must use all of the above requirements to generate more streamlined processes that lead to zero emission buildings. These processes will employ better interdisciplinary work that maximizes the integration of new concepts and ideas into building designs. The solutions presented should not be viewed as a series of potential add-ons, but as fundamental changes in design strategy that will not just improve building performance, but also add new and interesting aspects to the ever-evolving potential expression in building aesthetics, and in the potential comforts that buildings can provide.

References


Reduce CO2 from buildings with technology to zero emissions


Chapter 7

7 Closure

7.1 Research Objective

An extensive assessment of the use of the concept of exergy for buildings has been made. Specific examples of the analysis and development of two building technologies have been presented; one shows the explicit use of exergy analysis for wastewater heat recovery, and one demonstrates the design of a new façade concept based on exergetic principles. These exergetic principles have been expanded into a new method of exergy and anergy utilization for buildings. Based on this method, the design of integrated building systems based on low exergy design can be implemented and significantly increase performance. Finally, in the context of potential improvements, the impact on the overall building sector is discussed. This supports the motivation to reduce the environmental impact of the building sector due to greenhouse gas emissions.

The models that have been developed have contributed to the use of exergy analysis for building systems. The wastewater heat recovery model provided a unique exploration into the combination of stochastic heat recovery with a low temperature-lift heat pump. The active insulation system model and the overall integrated system model have shown how the concept of exergy generates levels of performance that are usually not even considered. The results of the exergy analysis will also support the work of others with similar objectives, such as Torio [1], who discovered unique added optimization potential for waste heat recovery when using exergy calculations instead of just energy calculations. The results provide the most direct evidence for the added benefit of exergy analysis for building systems, while the conceptual use for design integration provides a fundamental basis for its adoption in a methodological sense for building design.

The work played a contributing role in the international collaboration of the IEA ECBCS Annex 49 [2], supported by the Swiss Federal Office of Energy. It provided an international framework to position the objective of exergy analysis of building systems. The international collaboration also provided a network of feedback to help the work further its objectives and to meet new challenges. The network expanded the impact of the research while also contributing to its development and the overall object of exploring the use of exergy analysis for buildings. It provided a framework to compare models and methods and to exchange results and ideas.

The results of the modeling and the analysis of the building systems further generated progress in the expansion of low exergy systems and technologies, and provided examples of how exergy can be used both analytically and conceptually to develop better building systems. By striving to reach the objective of increasing building performance using the concept of exergy, a unique interface between the building design and building technology is created. At this interface, a common goal for both architects and engineers can be recognized that expands the architectural possibilities and increases the integration of engineered technology. By recognizing the performance improvements possible from integrated low exergy systems, the engineering limitations on the thermal performance of the façade are reduced allowing for high performance to be maintained with innovative architecture. More innovative architecture then creates a positive feedback that reinforces the integration of building systems. This self-reinforcing argument provides a fundamental support for this thesis, which argues for improved exergetic performance through systems integration.
7.2 Innovations

The work has developed and analyzed several new low exergy systems and combinations of systems for buildings. The wastewater heat recovery was accepted for an innovation great by the Swiss government for a public-private partnership to bring the system to market. Unfortunately the private partner was not able to follow-through and had to withdraw from the agreement. Nevertheless a novel system has been analyzed that shows the potential of decentralized heat recovery from wastewater. Even though it was not brought directly to market by industry, the work of the second paper in Chapter 2 (PLEA), led to the construction and installation of a pilot wastewater heat recovery system in a zero-energy house in Ireland [3]. It was highlighted on Irish national television [4], and is now described as the first net zero energy house in Ireland [5], Figure 7.1.

Figure 7.1 ‘illeedid’ house in Ireland. First net zero energy house in Ireland, which has incorporated the wastewater heat recovery system described in this thesis.

Exergy analysis has shown how wastewater heat recovery can help to achieve very high heat pump performance. It can lead to further reductions in heat demand from hot water production for high-performance residences where hot water aspects have great potential for further optimization. The potential was recently highlighted in an industry magazine [6]. The low exergy option helps move optimization of building performance to a level where supplying zero-emission renewable energy becomes much more feasible. It furthers the overall goal of achieving zero-emission building operation.

The development of the active low exergy geothermal insulation system (ALEGIS) created an innovative solution for integrated low exergy building operation. This proof of concept has generated a technology that reduces building heat demand without demanding thick insulation in the walls. It creates a unique solution that does not just reduce demand, but it also eliminates most of the variation in demand. This normalizing of the heat demand of the building helps to optimize the performance of an integrated heat pump system, which is unique to this system. Heat pumps are not ideal for managing variable loads, but can be optimized for performance with a constant load, and this is facilitated by the ALEGiS system. It provides a solution for high performance renovations where special, structural, or aesthetic restraints don’t allow adequate insulation installation. The system achieves a
performance during cold conditions that is equivalent to much thicker insulation installations. It was planned for installation on the B35 new construction project [7, 8], but the installation was too large and costly for an initial pilot so a smaller scale evaluation will be constructed first, shown in Figure 7.2. Nevertheless, the project was presented as part of an innovative building technology exhibition [9] shown in Figure 7.3, and has gained much interest as a novel way of thinking about building insulation.

Figure 7.2 Prototype ALEGIS system being installed on a historical building in Italy.

Figure 7.3 Demonstration wall for the ALEGIS wall installed at an exhibition in Germany [9]

Another innovative aspect of the research results was the development of a novel design perspective. The perspective included an expanded utilization of the concept of anergy sources to represent free sources from the environment, and the idea of utilized exergy to represent the final interaction of all building systems with the reference environment defined by the outdoor conditions. This has led to new developments in the building sector, both in terms of the technologies, and also in terms of the rules and regulations for building performance. The ideas of exergy and anergy optimization have supported the development of more low exergy technologies that can be integrated with low-temperature-lift heat pumps to achieve very high performance. The performance levels that
have been described are in fact, themselves unique. They have been shown to be possible in experimental operation, and there is significant interest in seeing how high a degree of a performance can be achieved as more and more pilot projects are initiated and completed that combine the latest low exergy systems. The first system with the new hybrid photovoltaic system and dual zone borehole will come online before the end of 2011 in the B35 building [7, 8]. It will be a first step in the expanding use of low exergy building systems.

7.3 Implications

Ideally, the major implication for the application of exergy to improved building systems will be the growing use of low exergy systems that will reduce the greenhouse gas emissions due to building operations. In the end the goal should be zero emissions from building operation, and this should be feasible with a smart combination of adequate building design, thermal performance, renewable energy utilization, and active low exergy system integration. The concept of low exergy active design has already led to new perspectives within the Faculty of Architecture and the ETH Zurich. A statement was published by the department about moving “Toward Zero Emission Architecture,” which relied heavily on the ideas of active low exergy systems.

The use of exergy analysis in buildings has been shown to be very useful, both in system evaluation and modeling, as well as in the overall design of buildings. It has been used in several projects. The field of exergy and buildings is expanding, both in academic research and publication, as well as in practice and implementation. This work should provide the basis for further analysis of the potential of building design.

A large reduction in the energy demand of the building sector can be achieved by utilizing integrated low exergy systems for buildings. Even more benefits can be achieved by combining the concepts of low exergy systems with the considerations for grey energy and emissions and the end-of-life of the materials supplied to the building sector. Low exergy systems can play an important role in helping move toward a built environment that not only sustains our current lifestyles, but that is also inherently sustainable.

7.4 Outlook

7.4.1 Changes in Regulation

The concepts of low exergy design have recently begun to play a role in the regulatory and political sphere of Switzerland. It has not been the specific application of exergy as a thermodynamic tool, but the supporting idea of reducing the quantity and quality of resources consumed instead of focusing only on end use demand and efficiency. For example, in 2008 the Energy Strategy of the ETH Zurich shifted away from the concept of a 2000 W society where everyone’s end use of energy consumption is limited, to an idea of a 1 ton Carbon of CO₂ emissions limit [10]. A limit of equivalent CO₂ emissions can be achieved with a wide range of different levels of energy use as shown in the plot from the energy strategy in Figure 7.4. The energy use can actually be expanded while CO₂ emissions are reduced through the implementation of low exergy design concepts that take advantage of free anergy sources and offset CO₂ generating combustion sources. The amount of CO₂ generated per capita can also be expanded to encompass many further indirect impacts from material and infrastructure utilization. There is a more flexible path for the world’s developing countries and the developed world to achieve a more sustainable society. Within this path, the ideas expressed here about the exergy analysis for improved integrated
Building systems fit well. They can play a beneficial role in moving this strategy forward and contributing to more sustainable development.

![CO₂ emissions graph](image)

**Figure 7.4:** CO₂ Reduction as part of the Energy Strategy for the ETH Zurich [10]. The plot is similar in concept to the NSE diagram presented in Chapter 6, and gives an example of how consideration for the overall effectiveness of energy usage can be improved without simply limiting the quantity consumed.

The broad contributions of low exergy systems to global sustainability are important, but they are not directly quantifiable. The shift of the broad focus on energy to a CO₂ limited society can benefit from exergetic concepts, but the strategy does not require an explicit declaration of the tools used for exergy analysis. Within the building sector, declaration of the benefits of exergy analysis can have a more direct impact. Regulations in the building sector that consider the quality and true value of energy sources can explicitly improve the performance of this sector.

The potential changes to the regulatory framework in Switzerland were discussed as a part of the impact of the perspective on exergy, anergy and the reference environment presented in Chapter 4. Although the ideas presented for zero emission architecture at the ETH [11] were initially met with some harsh criticism [12], the current outlook is for many changes to happen in the building regulations in Switzerland [13, 14]. Geneva already has a regulation for energy supply based on the concept of exergy [15], but the ideas for buildings currently being argued go beyond simple calculation methods. There are new ways of defining proper ways energy is incorporated into the design process itself. It fully incorporates the exergetic thinking discussed in this thesis. Most recently, the design process that is being used at the B35 project [7, 8] has been prominently publicized on the back cover of the NZZ [16] and included in a feature article in the Beobachter [17]. The expansion of these concepts generates pressure for standards like Minergie to address aspects that go beyond the final energy use of a building [18]. Currently low exergy concepts are not often addressed properly in some prescriptive aspects of Swiss regulations and standards. The potential adaptation of standards like Minergie has major future implications for the use of low exergy concepts. The changes necessary influence fundamental design practices and ideas that have been the standard for many years. A shift is occurring that may create a mindset that takes into account both the first and second law of thermodynamics for buildings. A mindset like this will actually create more freedom in design, and facilitate an integrated view of building design and system integration.
7.4.2 Future Work

A major area of analysis that has not been considered for low exergy systems in this thesis is the aspect of low exergy systems for cooling and dehumidification. These aspects must be considered to achieve a complete view of building performance, and will certainly be an area for future design and analysis work, that will result in more new building concepts and technologies.

Research into low exergy heating systems and heat recovery systems presented in this thesis was mostly based on the heating demands in the Swiss climate. The area of cooling must be considered for a global perspective. That area of researched will be continued in the hot and humid climate of Singapore for the SEC Future Cities Laboratory project [19, 20]. The Low Exergy Module within the Future Cities Laboratory will be coordinated by Forrest Meggers in collaboration with Prof. Hansjürg Leibundgut and Prof. Arno Schlueter, and it will provide an ideal test bed for adapting and optimizing low exergy technology and designs for cooling and dehumidification applications. The goal is to prove that integrated low exergy systems can also play a role in real projects in Singapore that are striving to reduce greenhouse gas emissions generated from the buildings.

7.5 References

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