ABSTRACT
The present paper deals with modeling of various low-exergy system components and their integration into the energy system for buildings and small communities. The exergy content of a certain amount of energy is defined as the part of this energy that can be used to produce mechanical energy. The quality of a certain amount of energy is defined as the relative exergy content of this energy. Most of our buildings with their heating and cooling systems today are built for conversion of high quality energy sources to low quality use with a huge destruction of the available exergy as a result. Globally we have a huge potential for transforming our processes to more efficient use of the exergy and also for feeding our processes directly from renewable energy sources without the use of high quality energy sources.

To develop our building concepts towards a low exergy building we have to analyze all the processes for energy conversion that take place through the operation of the building, to bring down the needed level of quality for the energy used and then make a holistic analysis of the system. Different processes for energy conversion in buildings are discussed especially giving the potential for saving energy and shifting the energy use to lower quality levels, i.e. in many cases to reduce the temperature levels needed for heating and cooling. The major obstacle for an extensive and effective use of renewable energy sources is the investment needed to be able to store heating and cooling energy in time. The paper gives a system concept under evaluation were the ground under the floor slab on grade is used as heat reservoir for the building. The main advantage of the system would be lower investment cost and at the same time give possibilities more effective annual storage compared to a single borehole. The paper also exemplifies how recent finite element technology where multiple physical phenomena can be studied simultaneously can be utilised for design of low exergy components.

KEYWORDS
Low-exergy, buildings, components, system, integration, modeling

INTRODUCTION
The present paper deals with modeling of various low-exergy system components and their integration into the energy system for buildings and small communities. The exergy content of a certain amount of energy is defined as the part of this energy that can be used to produce mechanical energy. The quality of a certain amount of energy is defined as the relative exergy content of this energy.

In recent years there has been a renewed focus on the energy use in buildings and since energy use is the dominating factor in the environmental impact of buildings the sources of energy also have to be evaluated from an environmental point of view. By shifting the use of fuel i.e. from coal to natural gas the general emission of pollutants have been reduced. The emission of CO2 however is still a problem that has to be solved. The available alternatives are biofuels, nuclear power and the use of renewable energy sources such as solar-, wind- and wave energy and hydropower. There seems to be a
worldwide consensus that the use of nuclear power should be limited and biofuels are in reality a high exergy source suitable for use in the transport sector. Besides that biofuels will always have limited global capacity since they are competing with the production of food and forestry products. Compared to industry and transportations buildings are very suitable candidates for the use of renewable energy. The solar energy hitting the ground is a high quality energy that can be converted to heat at very high temperature levels, to biofuels by photosynthesis or directly to electricity by a photovoltaic cell. The conversion of solar energy to a low quality thermal energy, sensible or latent heat is however, at present, by far the most economic way to harvest solar energy.

Most of our buildings with their heating and cooling systems today are built for conversion of high quality energy sources to low quality use with a huge destruction of the available exergy as a result. Globally we have a huge potential for transforming our processes to more efficient use of the exergy and also for feeding our processes directly from renewable energy sources without the use of high quality energy sources. For this we need new strategies for the energy systems in buildings that in simplified terms can be described to limit as possible the temperature differences needed as inlet temperatures for heating and cooling, (Schmidt 2004). As an example can we chose between electrical resistant heating, high temperature hydronic radiator heating with temperatures 80/60, low temperature radiators with temperatures 55/40 and a radiant floor heating system with temperatures 35/28 °C.

The reduction in quality immediately reflects on the available energy sources and the economy of the system. To produce hot water at 80 degrees and below we can use relatively simple solar collector panels but as we normally have to store energy from periods with solar radiation to the darker and colder periods our storage capacity for energy will increase approximately linearly with the temperature difference of the thermal storage and the lowest inlet temperature for the heating system. For the development of low-exergy components for heating and cooling of buildings we have to consider several things.

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LOW ENERGY HOUSES – TECHNOLOGY FIELDS

Thermal insulation of the envelope

The performance of the generally used standard thermal insulation materials such as mineral wool and expanded polystyrene has been only slightly improved over the last 50 years. New better insulation materials such as polyurethane have had relatively small market share due to a more complex chemistry with consequences for environmental impact and fire performance. The thermal performance of insulated constructions has mostly been improved by increased insulation thickness, better airtightness to avoid convection loss and improved construction technology to reduce thermal bridges. Recently we have seen the development of vacuum insulation panels and their application in building applications. These panels have 8 times higher thermal resistance for the same thickness as mineral wool. They are still far too expensive to be able to compete with conventional insulation of normal constructions but when lack of space or the architecture limit the available thickness they can become an interesting alternative. For vacuum panels with metallized plastic foils the main drawback is the limited gas tightness of the envelope resulting in loss of vacuum and reduced thermal resistance with time. For metallic enclosure the thermal bridge at the edges can considerably reduce the overall performance. Further development possibilities to overcome these obstacles are outlined in Thorsell.
Vacuum insulation is also an interesting alternative to improve the performance of appliances such as refrigerators, for smaller thermal storage tanks and to reduce heat loss from pipes and ducts. Window insulating glazing has had a very interesting development over the last decades. The introduction of low emission selective coating and inert gases in the air gap between the panes has resulted in reduction of the U-value for a double glass pane to one third of the original value. Development of window panes with vacuum or with transparent insulation such as aerogel have still not led to commercial products for buildings.

**Daylighting and control of solar gains**

With better performance of the window glazing the architects have seized the possibility to increase the total glazed area of the envelope without exceeding the overall energy budget for the building. This can lead to better daylighting and decreased need for artificial lighting but on the other hands this creates increased maximum heating load, increased solar gains with high indoor temperatures and increased need for cooling. Solutions for efficient control of solar gains to provide passive heating wintertime and reduce the cooling need in the warmer part of the year are of importance.

**Thermal inertia**

One of the simplest ways to utilized low quality energy is when we move heat in time from periods during the day with surplus heat during the day to the night when we have heating need or in the inverse way for cooling by simply storing the heat in the build structure. (Jóhannesson 1981) The ability to store heat over time is depending on the time constant of the building that is the ratio between the effective heat capacity of the built structure and the heat loss coefficient for the building. The difference in space heating energy for building with low and high time constants in North Europe can be of the order of magnitude 2-10 % (Kalema et al 2006) depending on house design and climatic conditions. For cooling the difference in energy use can be higher especially when forced night ventilation is used in climates with relatively large temperature variation. By exposing the surfaces with high thermal capacity to the indoor climate the effective heat capacity is increased. The introduction of phase change materials in constructions to utilize the latent heat for ins an interesting field of development which has been investigated for decades without a real commercial breakthrough due to technical problems based on limited heat transfer within the material units and a rather large transition temperature range. The performance of such materials by volume for thermal storage is at present for normal temperature variations in a room ca two times better than for the same volume of water.

**Ventilation – heat exchange**

By bringing the ventilation rate to a minimum the ventilation heat loss is reduced, the mechanical energy needed for the exchange air rate is reduced and the investment for the air exchange system is brought to a minimum. (Karlström and Jóhannesson 2006). The most effective means are to reduce the emissions of contaminants from e.g. smoking and building materials and to improve the ventilation efficiency. Demand controlled operation of the system in time can also reduce the energy loss. The air exchange can also be means for dehumidification and cooling and has in these cases to be valued against other means for the same purpose. One of the most common low exergy applications in buildings is air to air heat recovery from exhaust air to inlet air. The temperature efficiency is for recent applications as high as 85%. The exergy efficiency for this application can be seen in two ways

If we assume that the zero process would be balanced ventilation without heat exchange the energy efficiency can be calculated as
\[ \zeta = \frac{\gamma \cdot \Delta T \cdot \rho \cdot c \cdot V}{\Delta P} \]  

(1)

If we assume a constant outdoor temperature during the heating season to be the same as the reference temperature for the exergy analysis and neglecting the corresponding exergy efficiency becomes, (Shukuya ans Hammache 2002)

\[ \zeta_{EX} = \left[ \frac{\gamma \cdot \Delta T - T_{ref} \cdot \ln\left( \frac{T_{ref} + \gamma \cdot \Delta T}{T_{ref}} \right)}{\frac{\Delta P}{\zeta} \cdot V} \right] \cdot \rho \cdot c \cdot V \]  

(2)

Assuming the reference temperature at 273.17 K and the temperature difference between in and outdoor air to be 20 K, the density of air \( r \) 1.25 kg/m\(^3\) and the specific heat of air c as 1005 J/kgK the loss of pressure head in the heat exchange unit in both directions to be 100 Pa and the temperature efficiency for the inlet air \( \gamma \) to be 0.85 and the fan efficiency \( \xi \) to be 0.25 the energy efficiency \( \zeta \) becomes 53 but the exergy efficiency \( \zeta_{EX} \) becomes 1.6. If we however would have heat recovery as the only motive for the ventilation system i.e. we would consider natural ventilation as the zero process and the total pressure loss for in and outlet air in the ventilation system would be 500 Pa, the energy efficiency would be 10.6 and the exergy efficiency would be 0.32. We should bear in mind that the exergy efficiency for a heat pump system emitting heat to the indoor air to compensate for the ventilation heat loss with the outdoor temperature as source has an exergy efficiency

\[ \zeta_{EX} = \left[ \frac{\gamma \cdot \Delta T - T_{ref} \cdot \ln\left( \frac{T_{ref} + \gamma \cdot \Delta T}{T_{ref}} \right)}{\frac{\Delta P}{\zeta} \cdot V} \right] \cdot \rho \cdot c \cdot V \]  

(3)

and if the COP is 4.0 the exergy efficiency becomes 0.14.

From an analysis as above we can draw the following conclusions.

1. Air to air heat recovery is from an exergy point of view competitive to heat generation with heat pumps.
2. Reduction of head loss in the ventilation system and improved fan efficiency is the most effective way to improve the exergy efficiency.
3. Better temperature efficiency for the heat exchanger at the cost of an extra pressure loss might reduce the exergy efficiency

An interesting application of the exergy analysis would also be to try to foresee the long term advantage of natural or hybrid ventilation vs. full mechanical ventilation. From an exergy point of view it will be depending on the long term exergy efficiency of out heat generation system.

Lighting and applications

Only a small fraction of the electrical energy in a household is converted into light, sound or mechanical energy in processes where we need more or less pure exergy. The major part of the household energy goes to electrical resistant heating either due to bad efficiency as in light bulbs or because our appliances for cooking etc have the lowest production cost if we use direct electrical resistant heating for processes that require energy at considerably lower quality levels, such as the processing of food.
We see that lighting appliances, refrigerators etc have been developed for a significant reduction in energy and thereby of course the exergy consumption. From an exergy point of view we should also try to pair the applications with sources of energy with matching quality.

**Heat emission for space heating and cooling**

Floor heating is a commonly used low exergy application in buildings. The main incitement for the installation of floor heating has hitherto been the indoor thermal comfort rather than a conscious strategy towards low exergy systems. We have in recent years seen development of wall heating systems and also a rebirth of ceiling heating systems that with better insulation and reduced heating power load can provide both cooling and heating with good comfort. All these elements have also been used for cooling. As the power loads have been reduced we longer heat for keeping 20°C indoors but to provide thermal comfort. For that purpose we preferably should heat over large surfaces to use small temperature differences but at the same time concentrate our heat emissions to the zone closest to the outer walls especially those with large windows. With good radiation symmetry we will be able to keep the air temperature relatively low and thereby crate an ideal indoor climate for good comfort and health. Since the power loads are small it is a common misunderstanding that space heating can be provided with in a simplified way with back wall heating leading to increased radiation asymmetry or air heating with the hygienic air flow which can have significant negative effects on the thermal comfort as well as the ventilation efficiency.

**Heat distribution**

Heat is generally distributed as waterborne in pipes or airborne in ducts. The aspects that have to be considered are the heat loss along its path, the mass loss along its path, generally only applicable for air ducts and the loss of head pressure. The issues of insulation and tightness of pipes and ducts and pressure drop in ducts are common engineering skill but introducing the exergy concept into design will probably lead to larger dimensions of pipes and ducts since head loss is only overcome with mechanical energy.

**Heat storage**

Beside the short term heat storage in the building structure heat can be stored in insulated water tanks, insulated containers with phase change materials and in the ground. A common way to transfer heat to and from the ground is by coil either as a TR pipe in a borehole, Pipes down to aquifers or by horizontal coils in the ground. Usually these coils are mostly used as collectors to extract heating or cooling energy from the ground while the possibilities to store energy without to high loss demand a more sophisticated strategy with bundles of boreholes to get a reasonable relation between heat being stored and heat being lost. Even if heat can be collected in summertime at relatively low cost, auxiliary exergy is needed for the heat carrier to and from the thermal storage. In some cases a double use of the collector, i.e. for extracting heat in winter and cooling in summer is needed to restore the heat balance so that the average temperature of the mass around the collector will not drift outside the working range.

**Conversion of solar energy to heat**

Most of the solar energy hitting the ground is converted to heat at a temperature very close to the ambient temperature. In a solar collector we try to absorb as much as possible of the solar radiation using black surfaces and reducing the heat loss form these surfaces to the ambient by insulation on the back side and by transparent covering or glazing on the surface facing the sun. The heat carrier can e.g. be a air or water flowing in ducts and pipes with immediate thermal contact with the absorbing surface. Since the exergy of the solar radiation coming in is very high we can theoretically generate heat at very high temperatures. By focusing the solar radiation on smaller absorbing surfaces placed in vacuum
glass tubes with Low E coating and inert gases we can reach temperatures of several hundred °C. On the other hand simple uninsulated solar collectors can give large amounts of energy at low temperatures such as for heating of outdoor pools in summertime.

**Conversion of solar energy to electricity**

There are mainly three systems mentioned here. The most common one is using photovoltaic cells where the incoming light photons hit a semiconductor cell where the electron movements form an electric current. The next one is to use the solar energy heat a liquid with a relatively low boiling point and lead the resulting gas flow through a turbine for electricity generation, a third one that has been tried is to use the subtraction of memory metals that are alternatively cooled and heated to give a mechanical output. The methods to generate electricity with solar radiation are generally very expensive compared to what we buy from the grid and can only be economically motivated with heavy subsidies or for standalone applications where the cost in saved infrastructure is of high importance.

**Conversion of fuels to heat and electricity**

It is called cogeneration or trigeneration when heating/cooling and electricity is produced in an integrated process. Generally this is a way to maximize the exergy output when burning fuels and optimizing the process to meet actual needs.

**Heat pumps**

Heat pumps have already been mentioned above. As explained the exergy efficiency of heat pumps is limited even if the COP for energy can be as high as 4-5 since the process delivers low quality energy. Direct use of renewable energy from the source or from a storage is always to be preferred as long as the temperature levels are high enough.

**Economy**

Cost efficiency is a very important part of development. In the beginning we can claim that in a prototype stadium our solution will always be relatively expensive compared to what is common on the market. In the long run we will however to accept that the cost of the last saved kWh of exergy is a measure on how well we have optimized our system or if we have overlooked better and more economic alternatives to reach the same result. Also the money paid is a measure of our utilization of the global resources for our building and system. (Jóhannesson G. 2005b)

**LOW EXERGY HOUSE – A CONCEPT DEVELOPMENT**

**Annual storage on a single house scale**

Generally in mild temperate climates or colder all the energy needed for space heating and cooling can be harvested within the premises of a single building. The remaining problem is the storage of energy on an annual basis. Tanks with water or phase change materials would be large and costly to cover both the energy needed and their own heat loss. In modern Swedish buildings the floors are now very well insulated with more than 300 mm of EPS. The reason for this high insulation level is partly energy conservation, partly the urge to keep the ground plate free from moisture and partly a rational production of the in situ cast slab on ground with its foundation beams. More often the insulation is extended outside the floor slab to avoid frost penetration. The basic idea of this project has been to explore the properties of ground under a well insulated slab as a thermal storage. (Noguera 2007). The most obvious possibility is to put a hydronic coil in the ground under the building. We have however also noted that the washed gravel drainage layer under the house is very permeable for air and another possibility is to simply inject or extract air in an infiltration bed under the center or through the drainage pipes along the perimeter of the house.
The system concept

Figure 1. The concept with roof solar collector and ground storage under the floor slab, (Noguera 2007)

The heat is generated in a solar collector on the roof. The inlet heat carrier for the collector can be taken from the outside or from the perimeter of the storage. After the solar collector the heat carrier is pumped into the core of the ground storage. If heat is needed the heat carrier is either taken directly from the solar collector or from the core of the ground storage and heat is exchanged in three steps. In the first step for preheating domestic hot water and a low temperature heating circuit, in the next step to preheat inlet air and in the third step together with the heat from the exhaust air in a heat pump circuit that provides necessary temperature levels for the domestic hot water and the heating system. After this the heat carrier can be fed into the storage at the core or at the perimeter depending on the remaining temperature level.

Analysis

For the system design we need to design the components for our purposes but also to make a system analysis in time on an annual basis. The ground model so far has been modeled as a row house with a two dimensional structure where the temperature field is solved with finite elements in the frequency domain (Jóhannesson and Nilsson 2006) using a special application for the computer code COMSOL Multiphysics, (COMSOL Multiphysics 2007). The air borne solar collector has been modeled in detail

Figure 2. Analysis results from the left analysis of temperature along the roof part of the solar collector, monthly heat energy generated in the solar collectors with a 30°C minimum temperature and the amplitude of the annual temperature variation under the insulated floor slab, (Noguera 2007)
with convection flows, long and short wave radiation exchange and heat conduction with COMSOL Multiphysics. These results have been used to calibrate a simpler model based on the building simulation program CONSOLIS Energy+, (Jóhannesson 2005a) that has been used to study the energy production for different temperature levels and flows over the whole year. The energy need for space heating and domestic hot water have then been simulated by CONSOLIS Energy+.

CONCLUSIONS
The observations from this preliminary study are the following:

1. The air borne solar collector has to be fairly advanced, double glazed or similar to provide the necessary temperature levels to provide hot water during summer time and to bring the storage core to sufficiently high temperatures.
2. The heat generated in the solar collector has to be 4 times the energy need for space heating and DHW.
3. The insulation of the storage has to be extended some meters outside the perimeter of a normal house to provide the necessary storage capacity.
4. A more detailed modeling of the heat exchange in the storage is necessary to predict the part of the energy that has to be provided by the heat pump.
5. The auxiliary energy to operate the airborne system is estimated to be two times that of a normal balanced ventilation system.
6. The system is probably more feasible for cooling than for heating.
7. The investment cost mainly for extra insulation and solar collector should be similar to a system with a heat pump connected to an external borehole.

The work is planned to be continued with a more detailed simulation study and a full scale experimental study.

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