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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 3–6 to values ranging from 6 to 13.

1. Introduction and background

1.1. 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 utilizable 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 text books [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.

1.2. 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

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Nomenclature

COP	coefficient of performance
T	temperature of hot source or sink (K)
Q	heat (W)
W	work = exergy (W)
Ex	exergy = work (W)
An	anergy (W)
η	efficiency

Subscripts and superscripts

Carnot	ideal irreversible performance
hot	hot source or sink
cold	cold source or sink

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 Fig. 1. 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.

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 setup for heating, it moves heat from what we define as an anergy 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 $COP_{Carnot} = Q_{max}/W_{in} = T_{hot}/(T_{hot} - T_{cold})$. 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 anergy inputs, $Q = Ex_{in} + An_{in}$. As stated, the heat output is controlled by the COP, Q = COP Ex_{in}, where Ex_{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 anergy sources increases. Therefore we must find sources of sufficient quality, as well as with large enough quantity, which facilitated by considering freely available environmental anergy sources, as well as sources of waste heat from the building that would otherwise be lost to the environment [11].

By maximizing the anergy 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 anergy 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 radiant and 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 anergy source evaluation results in a system with low temperature-lift and a very high COP, which has the potential to provide a large amount of heating with little exergy input.

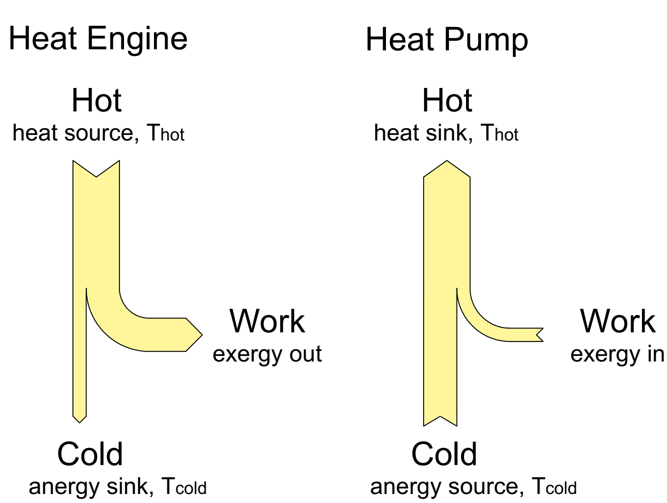

Fig. 1. The heat engine represents the origin of exergy analysis and the heat pump represents a principle component for exergy analysis of building systems. For both, the performance is dependent on the temperature difference between hot and cold.

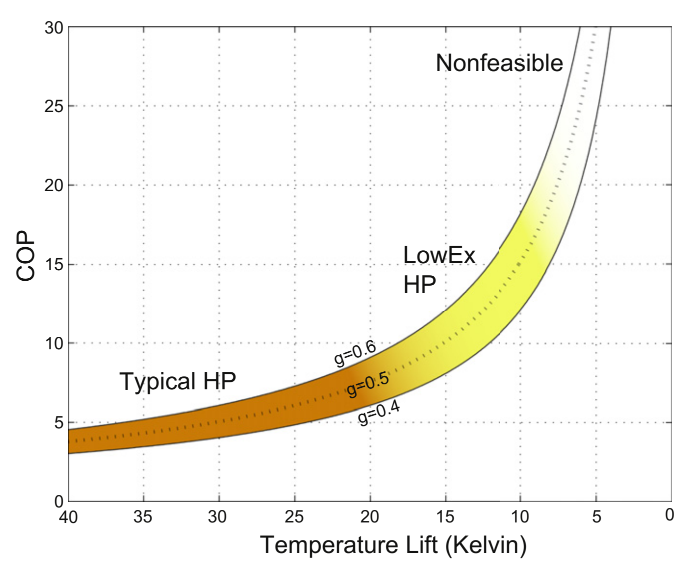

Fig. 2. Variation of COP with decreasing temperature-lift. Below temperature-lifts of 20 K the COP increases rapidly. A typical range from g = 0.4 to 0.6 for exergetic efficiency for existing machines are illustrated.

We illustrate the potential COP for a heat pump in Fig. 2. Real machines cannot operate at the ideal Carnot COP, but instead operate at some fraction of this ideal, usually ranging from 0.4 to 0.6. This represents the heat pump exergetic efficiency or "g-value", and it is a better indicator of the actual machine performance than the COP, because the COP depends on both the machine performance and the independent system temperature-lift. Even with typical g-values, it is clear that a much higher COP is possible as shown in Fig. 2.

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 anergy source. It is often possible to find anergy 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. As long as humidity can be controlled, radiant cooling can take advantage of the radiant heating supply structures, utilizing higher temperatures that reduce cooling supply temperature, 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 anergy 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].

1.3. Technology summary

As described, the heart of the system is a low temperature-lift heat pump. 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 or removal 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, 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.

2. Methods

2.1. Technology integration and evaluation

Fig. 3 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 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.

Heating and cooling are supplied to the structure from the heat pump, Fig. 3(d), connected to the dual zone borehole Fig. 3(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 Fig. 3(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

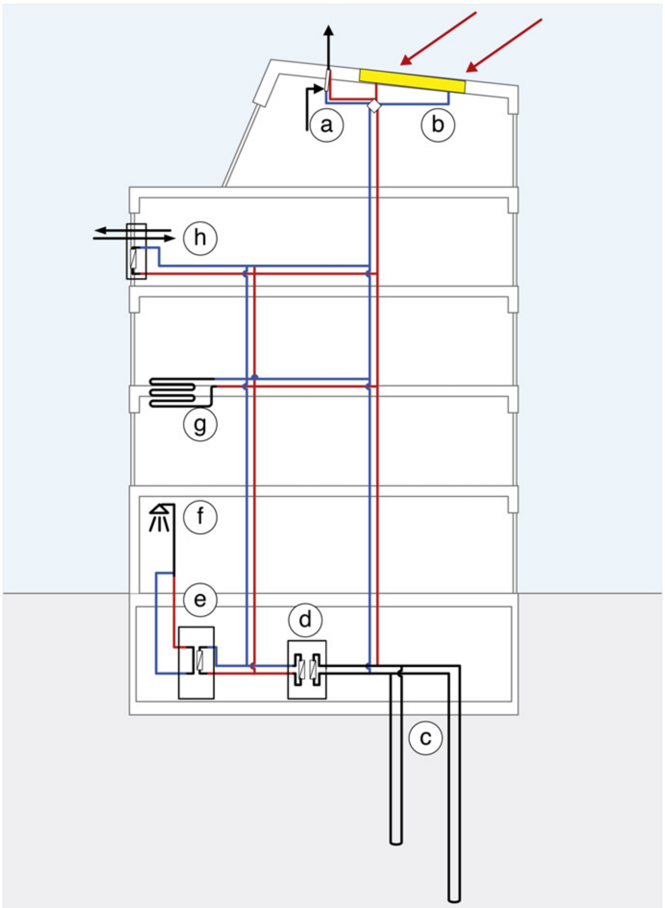

Fig. 3. Schematic of a low exergy system integrated into a building. The various components are illustrated: (a) Exhaust heat recovery, (b) PV/T hybrid panels, (c) dual zone boreholes, (d) high COP heat pump, (e) low temp hot water storage, (f) warm wastewater heat recovery.

optimize air supply and contaminant removal [29]. The exhaust is centralized and assisted by natural convection to exit through the roof, Fig. 3(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, where heat is recovered.

The decentralized air supply system, Fig. 3(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, Fig. 3(e), and heat from warm water usage can be captured for heat pump operation, Fig. 3(f).

2.2. PV/T prototype evaluation

We evaluated our PV/T panels mounted on the roof and connected to the hydronic loop as shown in Fig. 3(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 Fig. 4. With this setup different conditions were observed as the weather varied on the rooftop.

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.

2.3. 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

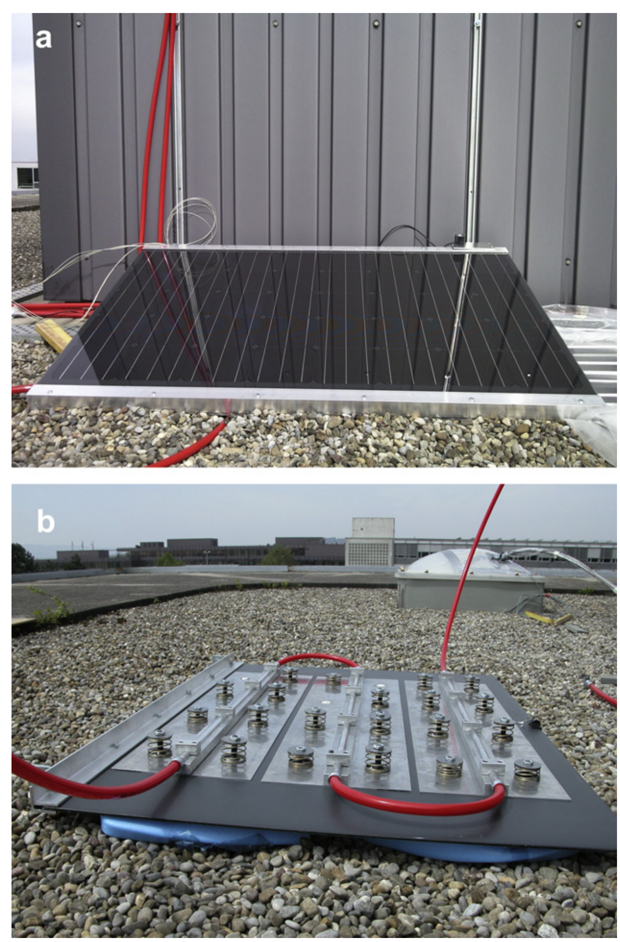

Fig. 4. Experimental setup fort he PV/T panels setup on the roof of the HPZ building, front (a) back (b). The panels were cooled with an experimental heat pump setup and the heat output from the system was measured during a variety of outdoor conditions.

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 (100 m/400 m), and a 450 m^2 array of PV/T elements in 15 parallel series of 26 mm 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 be capable of meeting the heat demand. The same heat pump as in the LowEx model was used to demonstrate the effect of temperature-lift shown in Fig. 2.

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 Fig. 3(c) is providing heat with a higher temperature to reduce the exergy demand for operating the heat pump in Fig. 3(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 10 × 10 m^2 two-story brick building in Zurich with an opaque façade U-Value of 0.5 W/m^2K and with 20% glazing having a U-Value of 1.0 W/m^2K.

3. Results

3.1. Building heating operation

The standard heating operation is illustrated in Fig. 5. The B35 pilot project will not have an annual heat demand less than 15 kWh/m^2 as stipulated by the stringent performance passive standards that focus on minimizing heat demand. Instead, an annual heat demand of 36 kWh/m^2 is predicted, but if the estimated minimum COP of 8 is achieved, the resulting annual exergy demand is only 8 kWh/m^2. 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].

In the heating mode, the heat pump is supplied by the deep borehole, Fig. 5(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 Fig. 5(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, Fig. 5(E). There are a variety of means of operation that we have included to

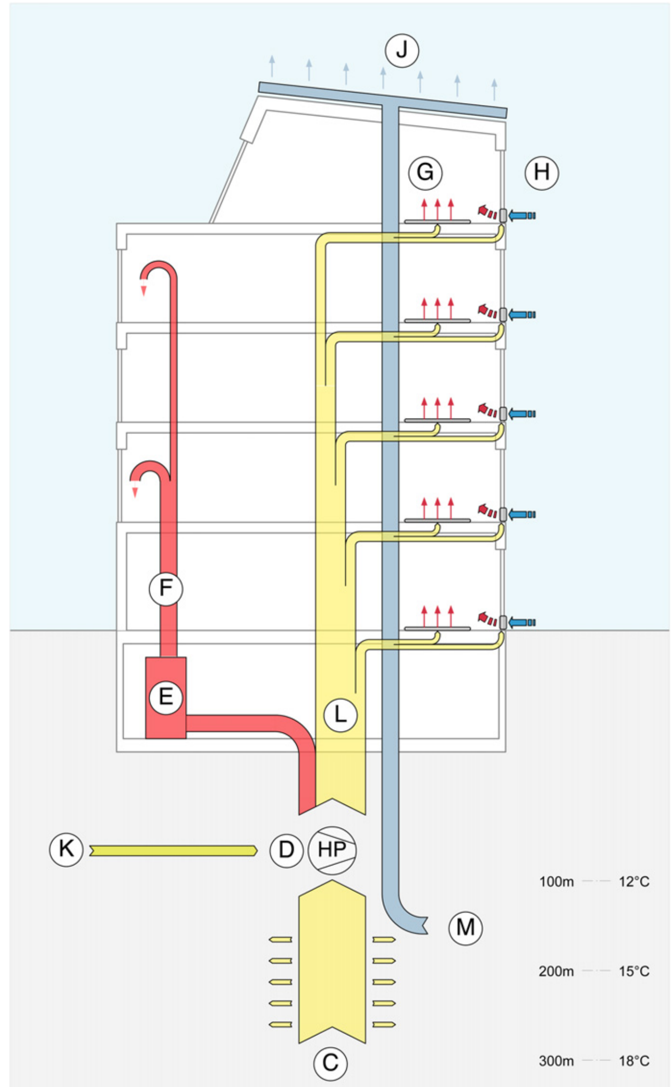

Fig. 5. Operation of the system during the heating season. Capital labels correlate to lower-case labels in Fig. 3 where applicable. The deep borehole (C) provides higher temperature base load heat to the heat pump (D), which can be supplied with a small amount of renewable energy (K) to produce low 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).

maintain a very low temperature-lift during hot water preparation. In the B35 pilot, the hot water is prepared at only 45 °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 45 °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, Fig. 5(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.

3.2. 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 temperature from the shallow borehole and can also be used to regenerate the deep warm borehole, as illustrated in Fig. 6.

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, Fig. 6(M). At this temperature, direct cooling of the structure is possible, Fig. 6(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, Fig. 6(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 Fig. 6(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. What would be considered overheating from radiation is now an anergy source. Excess radiation striking the floor behind a window, shown by Fig. 6(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.

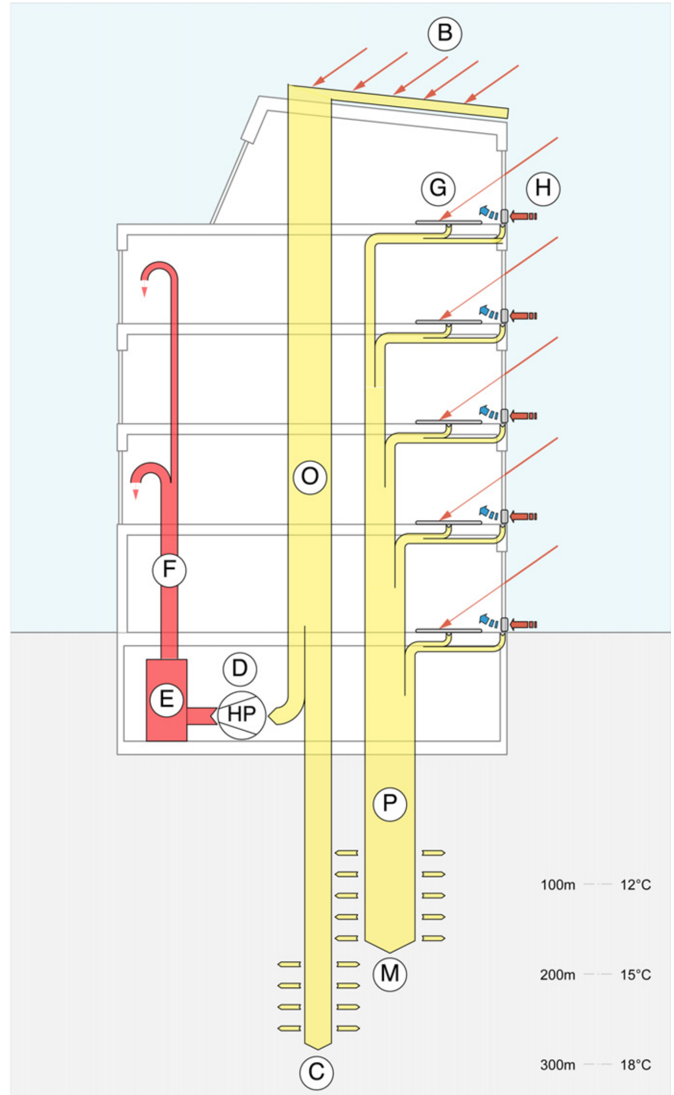

Fig. 6. Operation of the system during the cooling season. Labels again correlate to Figs. 4 and 5 where applicable. The shallow borehole (M) absorbs heat to provide direct cooling at around 10 °C (P) to the thermal mass (G) and decentralized air supply (H). The deep borehole (C) is regenerated by excess heat around 30 °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).

3.3. 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 10–16%.

Our experimental analysis on 1.66 m^2 PV/T panel showed a peak thermal performance of around 860 W (520 W/m^2) and a peak electrical performance of 230 W (140 W/m^2). This is a thermal efficiency of around 50% and an electrical efficiency of 15%. 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 Fig. 7.

The laboratory tests of 1.58 m^2 test panel with simulated wind showed that the thermal performance with a control input of 800 W/m^2 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

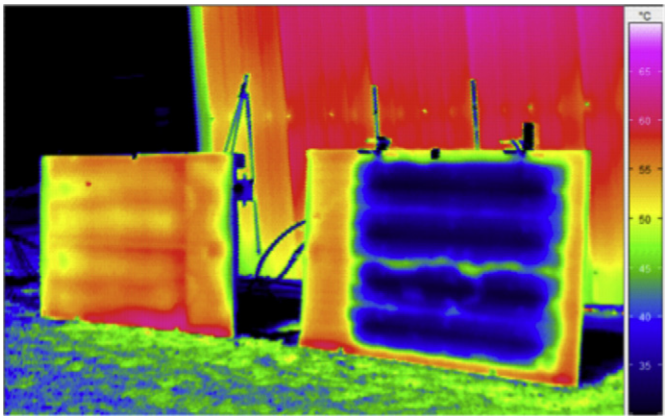

Fig. 7. Thermal photograph of the experimental PV/T on the roof of the HPZ. The panel on the left has no heat removal and a surface temperature ranging from 50 to 65 °C. The panel with the heat exchanger active has a surface temperature that is reduced to below 35 °C and an increase in electrical efficiency of 25%. Laboratory results showed an increase of 12%.

supply, and if electrical efficiency is improved or a COP greater than 10 is achieved, as has 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 Fig. 6 should accomplish a COP of about 15 according to Fig. 2.

3.4. 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/m^2 of usable floor area whereas in the LowEx model's old facade still demands 50 kW h/m^2. During the cooling season the LowEx model has a lower cooling load of 44 kW h/m^2, than the non-LowEx with 47 kW h/m^2 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 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 m^2 system, and for 3200 h of operation, the energy demand was only 1 kWh/m^2 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 to 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].

3.5. 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/(m^2 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 active and passive strategies for building operation with the same operational costs, the option with the lowest investment is not aligned with the option that achieves just a low passive heating demand. Still, 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 that when the investment split between a borehole and insulation is 87.5% for the insulation, The Swiss Minergie Standard of 38 kWh/m^2 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.

4. 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 for 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. 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 CO_2 emissions, and will move us down the path toward zero emissions for the building sector.

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