Reduce CO2 – With technology to zero emissions

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Prof. Dr. Hansjürg Leibundgut, Head of the Building Systems Group at the ETH Zurich, along with assistant Forrest Meggers, coordinated a unique collaboration with experts in architecture and engineering from around the globe to produce a draft paper on reducing CO2 emissions from buildings. Sheila Kennedy of the USA, Menghao Qin of China, Mike Schlaich and Werner Sobek of Germany, and Masanori Shukuya of Japan participated in an online forum during the 2nd half of 2009 to generate the foundation for this paper. This included online conference calls and 'Webinars' to review material and progress, allowing near direct interaction without travel-induced emissions.

The result of this experiment is a succinct draft summary paper for the Holcim Forum workshop, "Reduce CO2 – With technology to zero emissions," which covers the wide range of challenges to reducing emissions from building construction, operation and maintenance while also presenting an array of potential solutions. Not only that, this collaboration will allow this group of experts to come to the workshop already familiar with each other, and as a coherent team ready to initiate lively discussion and debate. This will help guide the entire workshop toward a broad consensus on reducing building emissions, which would then be generated at the workshop by an even larger field of knowledgeable participants.

The participants will be expected to review the draft paper and come prepared for a participatory workshop. The paper covers the overall problem of building emissions, both direct and indirect. The often-overlooked impacts of building material use are discussed. Also, the problems related directly to CO2 emissions and energy consumption by buildings are presented along with some 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. It is hoped that participants will be able to contribute here with other new and potentially significant ways to eliminate building emissions. The combined impact of the building construction, operation and maintenance makes it the largest singles sector in terms of CO2 emissions. This paper and interactive workshop will generate new perspectives, and thereby increase the potential to utilize new technology and to incite new government and industry policy that will reduce building CO2 emissions.

1 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 1940's, 1950's and 1960's. 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 [1].

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 [2].

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, 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. This includes finding new materials and methods to address the CO2 produced directly in building construction as well as reducing the massive amounts produced from the energy demand for 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.

Energy use by buildings is already often addressed, 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.

There is a vast potential in the integration of solar energy into the supply of energy to buildings. Both in centralized large-scale plants as well as in smaller decentralized systems directly integrated into buildings. 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 de-construction of buildings.

2 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 life spans 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.

Overconsumption of building materials must also be reduced. 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. Also, 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 [3]. 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.

One technological advance in lightweight structures is concrete with expanded aggregates. 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 [4]. 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.

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. 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 down cycling or waste.

3 CO2 Problem

The problem of CO2 emissions is at the core of the required 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 (Intergovernmental Panel on Climate Change, www.ipcc.ch) shows the importance of limiting the potential anthropogenic temperature rise [5], and the international community has agreed that it should not exceed two degrees [6]. 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 there is the possibility to have buildings with very near zero CO2 emissions from both construction and operation. 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.

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 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.

4 Analysis Methods

We have discussed the need to address grey emissions and the full influence of buildings on CO2 emissions, and 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. 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.

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.

This extension can be achieved with the concept of exergy, whereby both the quantity and the quality of energy are defined. Exergy differentiates 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. This 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 temperature and the second law, 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 [7]. By recognizing the potential of low-temperature-lift heat pumps, solar hot water generation becomes obsolete. Even with a low efficiency PV panel at 20% efficiency, connecting that 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 [8].

5 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.

But still, 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. 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. This all 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 to 10 Eurocent/kWh [9]. This 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.

* The contribution of “out of the box” ideas and concepts will be a key requirement of workshop participants. Hopefully the general ideas will only require minor modifications and they can be built upon here with real-world concepts and examples.

Figure 1: Solar updraft tower with high concrete chimney

Figure 2: Solar updraft tower, glass greenhouse

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. There is also still huge potential for expansion in wind energy and other renewable sources that are being researched such as tidal and geothermal sources.

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. 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. Also, 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, this 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 could utilize solar energy at a better combined efficiency using inexpensive PV technology and simple heat exchangers than much more expensive high-tech PV panels and vacuum-tube solar-thermal panels.

Technology transfer from existing industrial manufacturing to construction can also be considered. These include 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 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 CO_2/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 [10].

Still, 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.

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. 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. 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 also be reevaluated. 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"). 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 the first half centimeter of insulation 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.

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. Also, while storage helps generate a constant stable renewable supply, buildings can help even the load 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 delivering by a heat pump from the ground below to the surface for space heating. 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.

6 Impact of Solutions

The goal of our solutions for the field of building design and construction is to reduce the subsequent anthropogenic CO_2 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 CO_2 emission reduction that would otherwise be overlooked.

The CO_2 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 CO_2 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 also 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. Within the new analysis methods also 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. This includes 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.

We do not state a specific timeline for these goals to be met. We only recognize that the ideas and technologies are available and should be implemented as rapidly as possible. We will provide the knowledge, tools and technology to allow policy-makers to set the much-needed targets to prevent potential catastrophe caused by climate change.

We do not know how close we are to a tipping point. We hope the tipping point will not be one that leads to irreversible climate change, but rather one that leads to a revolution in building design and construction that opens new avenues of construction, materialization, and operation to create a future generation of buildings that make a zero-CO_2 built environment a reality.

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