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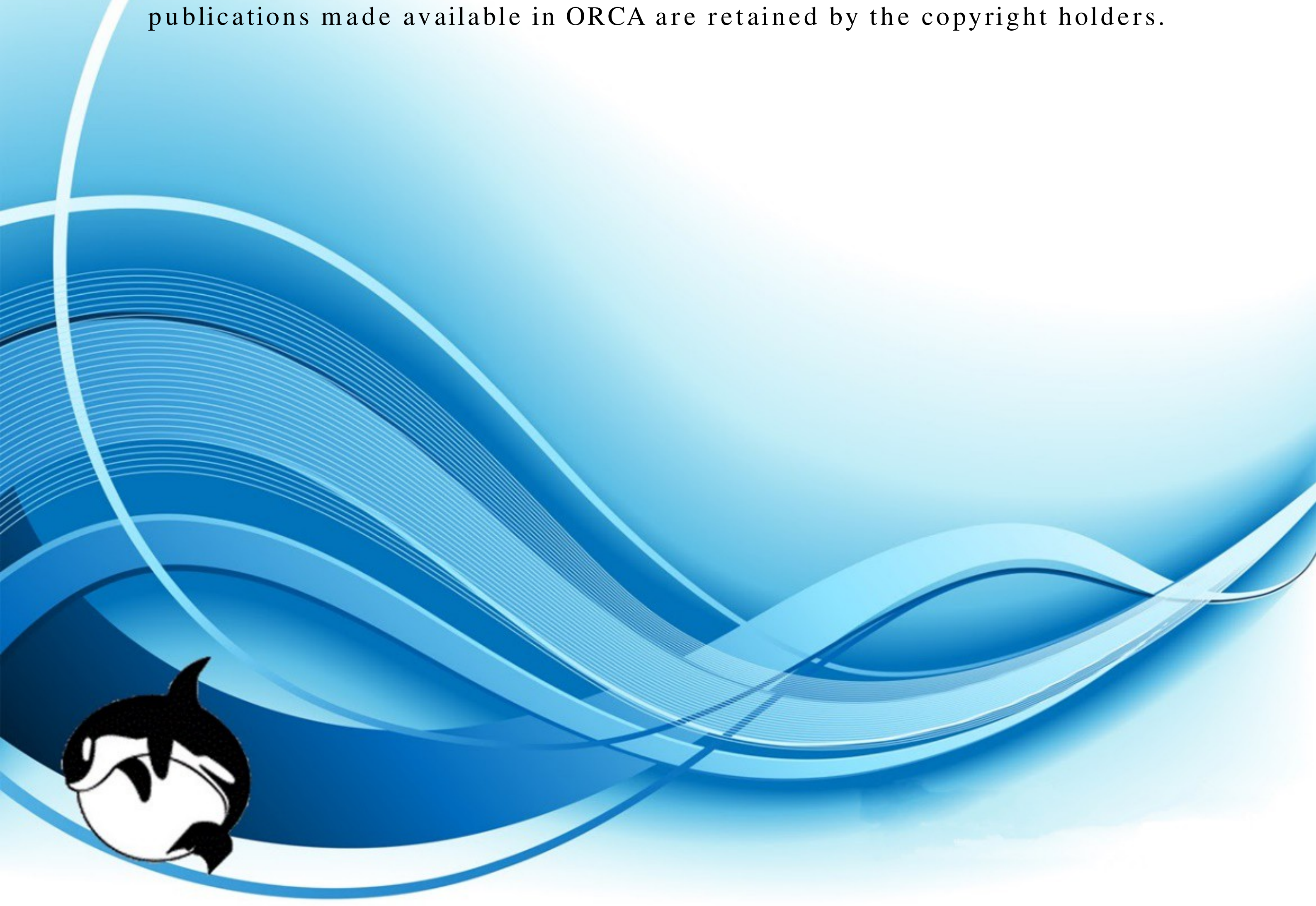

Towards zero carbon design in offices: integrating smart facades, ventilation, and surface heating and cooling

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Abstract: This paper discusses an overall strategy for reducing energy demand in non-domestic buildings, mainly focusing on office developments. It considers four areas: reducing internal heat loads; addressing passive design through the building construction; using efficient and responsive HVAC systems and focusing on chilled (heated) surface systems; integrating renewable energy supply systems into the building design. The impact on energy use and carbon dioxide emissions will be discussed. The paper will draw from a range of design projects carried out in Europe, where this integrated approach has been applied, and then explore the benefits in relation to applications in the Middle East and China. Energy modelling results, to inform the design process will be presented, using energy simulation for three case study locations, in Zurich, the Chongqing and Abu Dhabi.

Keywords: Building energy use, low carbon, energy simulation

1. Introduction

Reducing energy demand in buildings requires an integrative and holistic approach to all aspects affecting energy performance, whilst ensuring comfortable healthy conditions for occupants, and within the context of the local climate. Achieving a low or zero carbon building is a combination of reducing energy demand and providing energy supply from renewable sources. In many cases it may not be feasible to provide a totally zero carbon building, and the concept of a low carbon building might be currently more appropriate to provide a bridge to eventually achieving zero carbon performance within acceptable costs. This paper discusses the process of arriving at a low energy, low to zero carbon building design, using an office building type as an example. The paper takes as a baseline, typical European design standards and techniques, based on buildings that the authors have worked on. It then applies the same standards to China (Chongqing) and UAE (Abu Dhabi) in order to explore how these standards would compare under different climatic conditions. The paper discusses how energy demand can be reduced, and then how low carbon performance can be achieved through the additional application of renewable energy. The paper discusses the need for energy storage, if the renewable supply is building integrated, although in many cases energy exchange with the grid is often used in practice to achieve a ‘carbon neutral’ building.

2. Low Carbon Design

A number of design models have been suggested to help achieve low energy and low carbon design. They generally focus on the elements of design as well as the design process. One example, using an integrated design process was developed through the International Energy Agency’s Solar Heating and Cooling Programme Task 23 in 2003 (Larsson and Poel 2003) which was based on experience in Europe and North America. It consists of a series of design loops at stages of the design process, namely of, pre-design, concept design and design development. Performance targets aim to minimize heating and cooling loads, and maximize daylighting potential and the use of solar heat gains, together with efficient heating and cooling systems, and using renewable technologies to meet the energy demand loads. An iterative approach is used to produce a range of design alternatives, which are then tested through energy simulations. Another approach was developed by M-A. Knudstrup, Aalborg University, Denmark in 2004 (IEA 2006), which requires a description of the environmental or sustainable building concept at the first stage of the building project. Subsequent stages are developed around an Analysis phase, to provide a statement of aims, a Sketching phase, where the of architecture and engineering is integrated into the design process, a Synthesis Phase, to produce the building’s final form, and finally, a Presentation phase, where the project is clearly described for the building owner. The system developed by K. Steemers, Cambridge University, the UK, 2005, assesses the interrelationships and levels of integration of design parameters for low energy design in an urban context. It raises awareness of a range of environmental and design parameters rather than a rigid process, relating to the principles of low energy design. This is followed by steps for developing the pre-design context, the building design, and then the building services (IEA, 2006), with each phase broken down into aspects and sub categories. P. Jones, at Cardiff University developed an approach (Jones and Wang 2007), beginning with climate data to help define the design objectives, then to passive design strategies, from site planning, building form to building fabric, followed by energy efficient building services, with renewable energy systems used to supply energy required by the building systems (Figure 1). Also considered are waste associated with construction materials and products used, as well as waste generated in the process. Although there is no diagrammatic description of its links with process, the intention is that it is referred to at all stages, from concept through to detailed design.

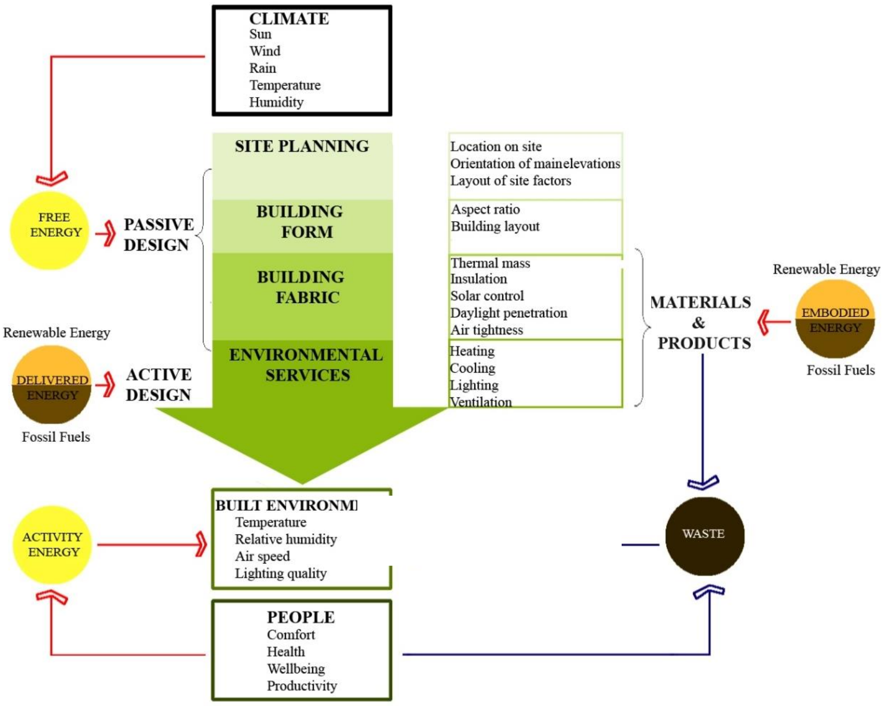


Fig.1 The model of low/ zero carbon design

The above design systems can be simplified for low to zero carbon design to include four steps, reducing energy demand, passive design, mechanical systems, and the renewable energy supply (Fig.2). In common with the above design systems, this simplified approach should be holistic, applied from the early concept stages of design, and tested through analysis simulation. The use of simulation should be to inform the design process, rather than dictate it, and therefore it should be carried out at early design stages. The four areas of the design process (Fig 2) are used as a basis for discussion in the following sections, with specific reference to office design. The discussion draws from experience of providing building physics advice to many design projects in Switzerland (in collaboration with Kopitsis Bauphysik Ag). This is followed by an example of building simulation of a typical office development in three different climate locations.

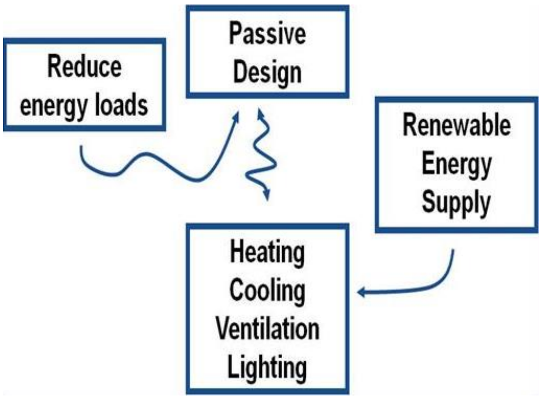


Fig.2 An approach towards zero carbon buildings

2.1 Reducing internal heat gains

The first step in any low energy design should be to reduce the electrical energy loads in the space, from lighting, small power (plug loads) and any other incidental energy use. This will have the added benefit of reducing the cooling load demand needed to exhaust the heat gains from this equipment. In locations requiring heating, these incidental heat gains can prove useful in meeting the space heating demand. However, for most modern office designs there is little space-heating requirement, and so these heat gains are not always useful. In many cases, even in cold weather, after initial warm up in the morning, active space-heating is not required. Table 1 presents typical ‘current’ good practice and ‘efficient’ loads associated with internal heat gains. In the table, ‘Current’ refers to design parameters that are currently generally recognized as energy efficient. ‘Efficient’ refers to design parameters with more advanced technologies, with improved energy efficiency, which are available but may not be so widely applied in practice. For example, the use of low energy computers and LED lighting can result on overall space internal heat gains as low as 18 W/m^2. The values are for an occupancy density of around 1 person to 12m^2, which would represent a typical design standard in Zurich (which is used as the basic standard for this study).

Table 1 Internal heat gains to space from ‘current’ good practice and ‘efficient’ design [1, 2]

Internal heat gains	Current (W/m^2)	Efficient(W/m^2)
Internal gain from people (~12m^2/person)	6.0 (sensible) 5.0 (latent)	6.0 (sensible) 5.0 (latent)
Plug load	10.9	4.9
Lighting	12.0	7.0
Total (sensible)	28.9	17.9

2.2 Passive design – smart facades

Low energy design should consider the passive design attributes that can be used modify the external climate to the benefit of improving the energy performance of the building, including orientation, solar control, daylight and use of thermal mass. Even in mechanically cooled and ventilated spaces, passive design can contribute to reducing energy use. The building envelope is a major part of the passive design approach, and, for modern office design, the use of ‘smart’ layered facades can provide for good thermal insulation, control of solar heat gains and daylight. Glazed facades can now be designed with high levels of thermal insulation (with U-values below 1W/m^2/^{o}C), effective solar control (g-values typically down to less than 0.15), and good visible qualities to allow for the use of daylight. Such facades can incorporate blind systems (Fig.3) located, externally, between pane, and internally, although the latter does not easily achieve lower g-values as the solar heat gain has already entered the space.

Examples of adjustable external and inter-pane blind systems are illustrated in Fig.4. The EMPA office in Zurich (Fig.4a) has external vertical diffuse glass blinds that move to accept daylight but control the sun (Jones, P. J. and Kopitsis, K. 2005). Ta-Media, also located in Zurich, has horizontal diffuse glass external blinds (Fig.4b), which are lowered when the solar radiation exceeds a specified value. The Hannover EXPO HQ has inter-pane blinds (Fig.4c). In general blinds located on the outside perform best in terms of reducing solar gains, although they may prove more difficult to maintain. Blinds located on the inside, and to some extent mid-pane blinds, generally do not perform as well because the solar heat gains have already entered the construction and will result in some level of heating the internal surface of the glazing/blind system. In general, the 'rule of thumb' adopted by the authors through design experience, is that the inside glass or blind surface temperature should be within 5^{o}C of air temperature, to maintain thermal comfort conditions. Although these glazing systems may be referred to as passive facades, they do include active features of moveable blinds. Facades become even more active if they include building integrated energy supply systems, such as discussed later in this section (2.4).

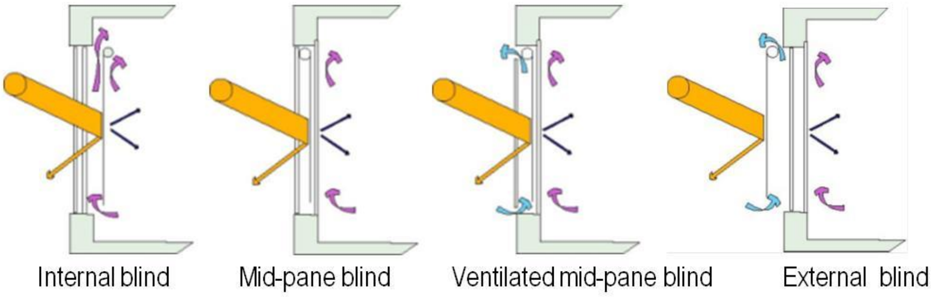


Fig.3 Range of layered glass facades incorporating shading.

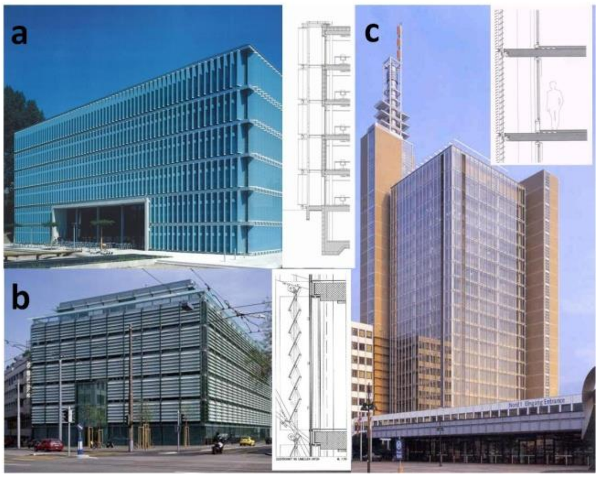


Fig.4 Adjustable external blind systems in (a) EMPA, (b) Ta-Media offices in Zurich, and ta mid-pane system in (c) Hannover EXPO HQ.

2.3 Heating, cooling and ventilation

Once the internal gains have been minimized and the building envelope has been designed to reduce heat loss and to control solar heat gains, the active processes associated with heating and cooling should become simpler and more efficient. The reduced energy demand loads, from internal and solar heat gains, make it easier to decouple cooling (and heating) from the ventilation system, using chilled and heated surfaces (usually the ceiling). This has been an area of major development in Europe. A traditional air-conditioning system would use the air supply as the cooling means, therefore requiring relatively large amounts of air delivery. Typical air supply rates for cooling could be 6ac/h or more, compared to less than 2ac/h if used for just ventilation. Fig.5 illustrates a comparison between an all-air system with a decoupled chilled ceiling system, indicating the level of reduction in internal heat gains and solar heat gains, through the above design strategy. As the proposed system does not require any air recirculation the ventilation air supply is 100% ‘fresh’. It also has the potential for improved comfort, with lower air volume flows (less draft) and cooler surfaces in summer (generally considered better for comfort). Dehumidification will often be required when the external relative humidity (RH) is high, and this can be achieved through the mechanical ventilation system, and as long as the façade is ‘airtight’, high external RH should not prove a problem.

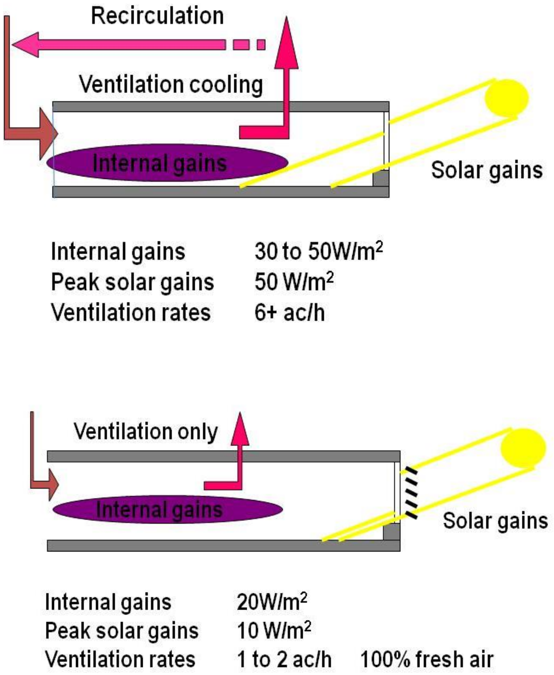


Fig.5 Comparison of a more traditional all-air ac system (top) with a ‘decoupled’ chilled ceiling system (bottom).

Fig.6 presents typical options for chilled surface cooling depending on internal loads. For lower internal loads, thermal mass with night cooling may prove sufficient. The chilled ceiling system, with embedded pipes in the slab, can satisfy typical use (~ 30W/m^2, as indicated in Fig.6). If there are areas with high heat gain, then a chilled beam solution might be more appropriate. However, the ceiling surface temperatures will be lower, typically 17°C compared to the chilled ceiling option of around 20°C, and so the potential risk of surface condensation increased.

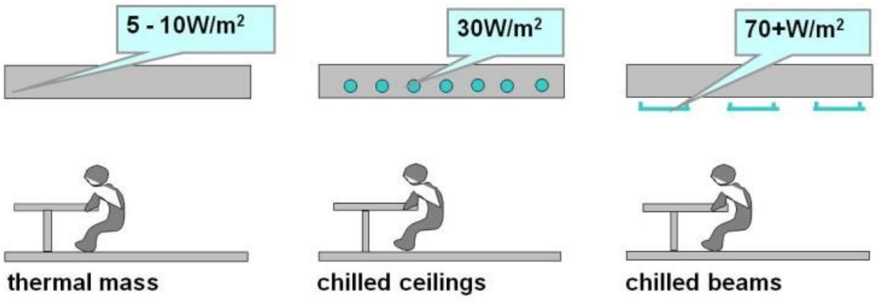


Fig.6 Chilled surface options: thermal mass (with night cooling), chilled ceiling and chilled beams.

The combination of the above design approach can result in: lower fan power due to the lower rate of mechanical air supply; higher COP values for cooling, due to the raised chilled water temperatures; better air quality, due to no recirculation needs and easier air distribution to the occupied zone; less space for plant, due to the reduced air handling equipment size; less space for air distribution, due to the reduced duct sizes (potentially reducing floor to floor heights); higher space use for occupants, due to the reduction in glare and greater solar control; greater comfort and more stable conditions, due to simpler controls. The main drawback is the need to control the RH of the supply air, especially for chilled beam systems, and in relation to this, ensuring an airtight façade system, to avoid the infiltration of moist air.

2.4 Renewable energy supply and energy storage

If the above low energy design process has been followed, then the energy demand for the building will be considerably reduced, making it potentially easier to supply the remaining energy from 'active' renewable energy systems, for both electrical and thermal energy. This will include the energy needed for cooling, heating, small power (plug load) and lights, which will depend on the building type, occupancy and location. The energy supply needed to meet the demand will depend on the efficiencies and COP's of the various environmental systems and the type of fuel used. Fig.7 illustrates the relationship between energy demand and supply, and also the link with CO_2 emission factors, which are used to provide the total CO_2 emissions for the operation of the building. The CO_2 emission factors will depend on the fuel type and the carbon content of the local grid, which can vary considerably depending on the nuclear, hydro and other renewable and 'zero carbon' contributions, or, whether the building has its own renewable energy supply. When describing the building performance, a clear definition of energy use and CO_2 emissions is needed, for example, whether quoted values (say in kWh/m^2/annum) refer to demand or supply, and do they include heating, cooling, ventilation (fan power), small power, lights, etc.

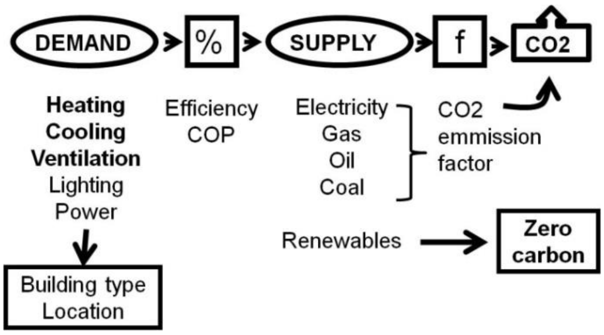


Fig.7 Relationship between energy demand, energy supply and CO_2 emissions.

In many cases renewable energy systems can be integrated into the design of the building envelope, such as transpired solar collectors (TSC's) for collecting thermal energy through south facing cladding systems for solar air heating (Fig.8a), or, such as encapsulating thin film PV onto metal roof cladding, or using glazed PV systems as the roof material. In some cases, solar PV systems can be used as blinds, such as in the office facades of the Baglan Energy Park 'Gateway' industrial building (Fig.8b).

The direct availability of renewable energy is usually dependent on the prevailing conditions, for example, solar and wind. So, unless some form of local storage is available, the grid will be needed to provide energy when renewable energy is not available. Net zero energy or carbon neutral performance may be achieved by input and export from the grid, often referred to as two-way flow.

(a) (b)

Fig.8 (a) Transpired solar collectors (TSC's) for collecting thermal energy through south facing cladding systems for solar air heating. (b) PV system used as shading device.

There is an increasing interest in energy storage systems, both thermal and electrical, to provide short and long term storage so that grid two-way flow is not needed. Grid back-up may still be desirable, for periods when there is no renewable energy supply and the storage has been exhausted. In some countries, exporting electricity into the grid is not allowed, so two-way flow is not applicable. Fig.9 illustrates systems for thermal and electrical storage, from a current project SOLCER (Smart Operation for a Low Carbon Energy Region) being carried out in Wales (EU ERDF funded), which is investigating the combination of reduced energy demand, renewable energy supply and energy storage at a range of built environment scales. So, a carbon neutral building is possible using two-way flow with the electricity supply grid, but to achieve a zero carbon building will require some means of energy storage.

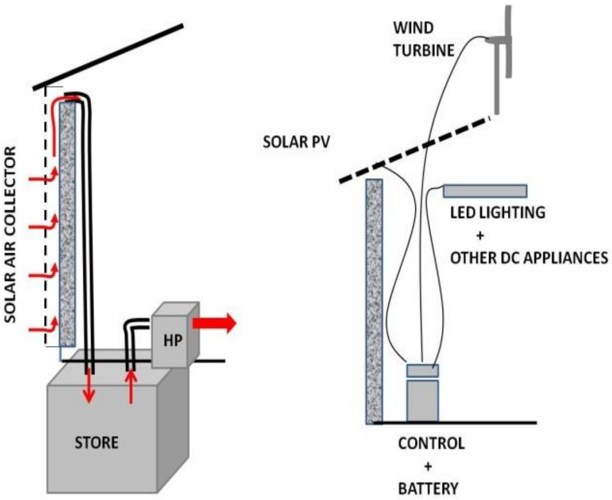
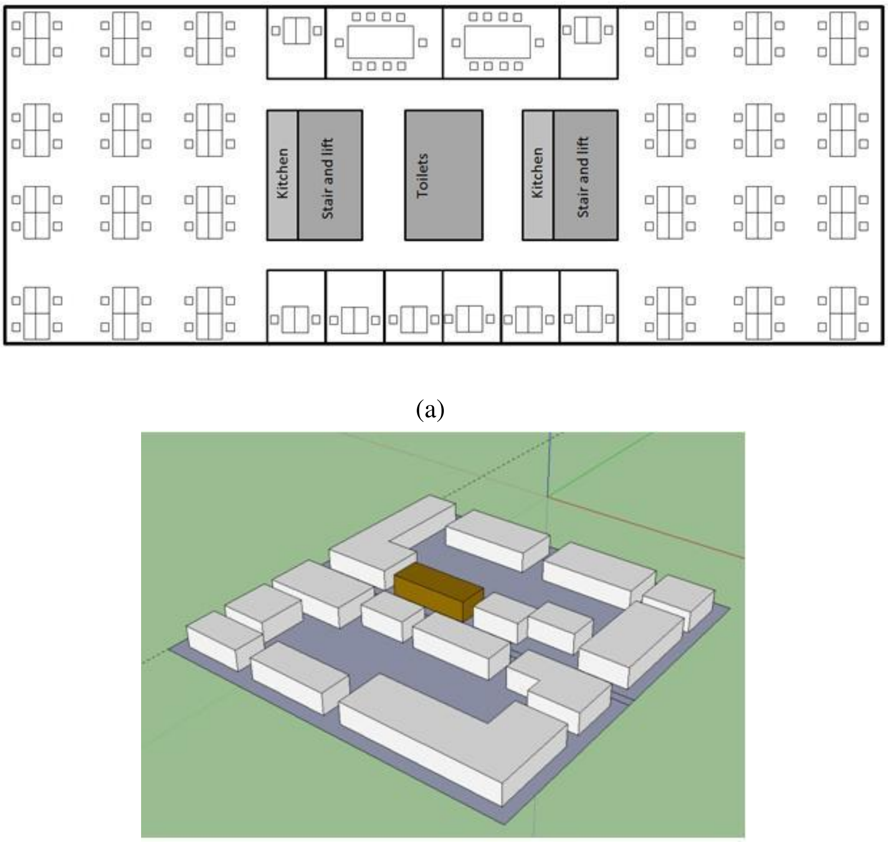


Fig.9 Example of building integrated energy supply and energy storage for a thermal system, using a TSC air collector, and an electrical system, combining solar PV and wind (SOLCER project, Wales Low Carbon Research Institute).

3. Energy simulation

The above section has described the process of 'low energy' and 'low carbon' design, based primarily on the office building type. The examples referred to in the above sections are from Europe, and especially based on experience of office design in the area of Zurich, Switzerland. The discussion of design models at the start of the previous section identified the need for early design stage simulation as part of the analysis process. This section presents an example of energy simulation that would be typical of that used in the design of a number of the above case study building design examples from Europe. In this study, the analysis has been extended, firstly, to consider applying European (Swiss) standards to two other locations, namely, Chongqing and Abu Dhabi, and secondly, to explore the energy demand and supply needs in relation to the availability of renewable solar energy. The aim of this simulation energy analysis is to determine if reducing energy demand then allows the potential for renewable energy supply.



(a)

(b)

Fig.10 Building simulated: (a) Plan of typical office floor layout; (b) Site plan.

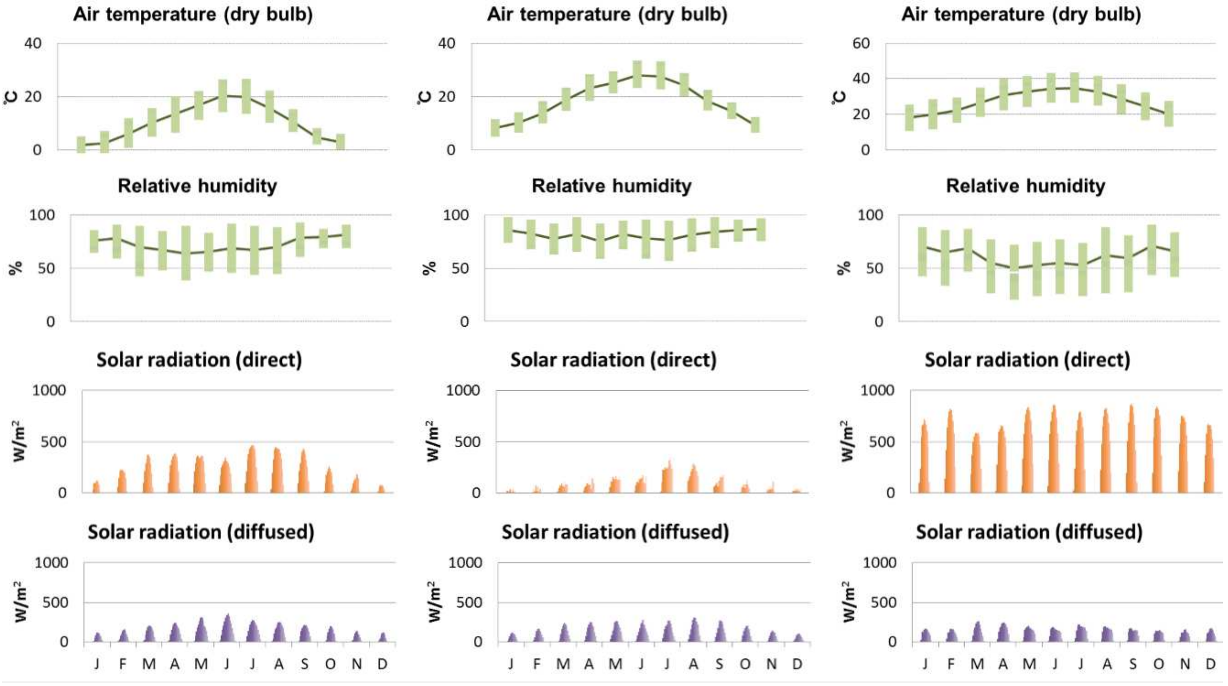
It takes as a basis for comparison a 6-storey office block (Fig.10a: typical floor layout) of overall dimension, 26m by 68m with a floor to ceiling height 3.0m. This hypothetical medium rise design, is typical of what might occur in Europe, placed in the context of surrounding buildings to account for typical overshadowing and its impact on energy performance (Fig.10b: site plan). The main input data used in the simulation it summarized in Table 2.

Table 2 Simulation input data

Internal gains (W/m^2)		Building fabric		Systems
Internal gain from people (12.2m^2/person)	6.0	External wall	U-value=0.17W/m^2/K	Mechanical ventilation 0.97ac/h at 18°C Operating 9:00 - 18:00
Plug load	4.9	Roof	U-value=0.17W/m^2/K	Cooling COP = 4; Heating COP = 3 Operating 9:00 - 18:00
Lighting	7.0	Ground floor	U-value=0.17W/m^2/K	Solar PV, 1768 m2 at 15% efficiency.
Total	18.0	Glazing	U-value=1.0 W/m^2/K; G-value=0.15 Window to wall ratio is 70%	

Notes:

a) The building is only used during workday, namely from Monday to Friday;



Zurich Chongqing Abu Dhabi

Fig.11 Weather data comparison for 3 locations (source: Energy Plus weather data)

b) The occupancy profile is set as: 09:00-13:00 100% occupied; 13:00-14:00 100% occupied; 14:00-18:00 100% occupied, which refers to the typical condition in Switzerland.

Fig.11 presents a summary of the monthly weather data used in the simulations for comparison; the actual simulation uses hourly weather data. The weather data for the simulation was obtained from the EnergyPlus weather database [Energy Plus weather data DATE]. The three cases represent a range of climates, from distinct seasonal conditions in Zurich, to warm humid conditions in Chongqing and hot desert conditions in Abu Dhabi. Chongqing has an interesting climate in that it is warm but often overcast with relatively low levels of direct solar radiation.

The simulation was carried out using the dynamic building energy model, HTB2, which has been developed at the Welsh School of Architecture (Cardiff University). It has undergone extensive testing, validation, including the IEA Annex 1 (Oscar Faber and Partners 1980), IEA task 12 (Lomas 1994) and the IEA BESTEST (J. Neymark et al 2011), and has been applied in many research and design projects (IEA 2006). HTB2 is able to simulate hourly annual energy and internal environmental conditions, based on the location's weather data, the building construction and layout details, the mechanical services and occupation profiles for people and equipment use. It is also able to account for overshadowing of surrounding buildings and landscape features. In the simulation used in this study, the mechanical services have been simplified using seasonal average values or COP, and PV efficiency. For comparison sake, the buildings are 'all electric' and heated and cooled using a heat pump. A constant outside air supply has been assumed for the mechanical ventilation system. The main focus of this paper is on the energy demand, as described in figure 7 above.

The results from the simulation for the monthly energy supply are presented in Fig.12. Figure 13 presents the annual demand and supply. The Zurich case has a relatively high heating demand and relatively low cooling demand compared to the other two cases. Abu Dhabi has no heating demand and a high cooling demand. The energy supply is estimated from the average COP values, which for this simulation are assumed the same for each location (table 2). In practice, they would vary depending on local conditions and load profiles, as would the efficiency of the PV system. However, the main purpose of this paper is to provide some initial estimates of the potential to meet the energy supply from renewables, in the context of reduced demand. The potential solar energy generation is seasonal in Zurich, with relatively high summer values. It is relatively low in Chongqing, due to the overcast nature of its climate. Solar energy potential is high throughout the year in Abu Dhabi. However, even for the relatively low case in Chongqing, he solar energy generated can meet the energy demand most of the year, on a monthly basis.

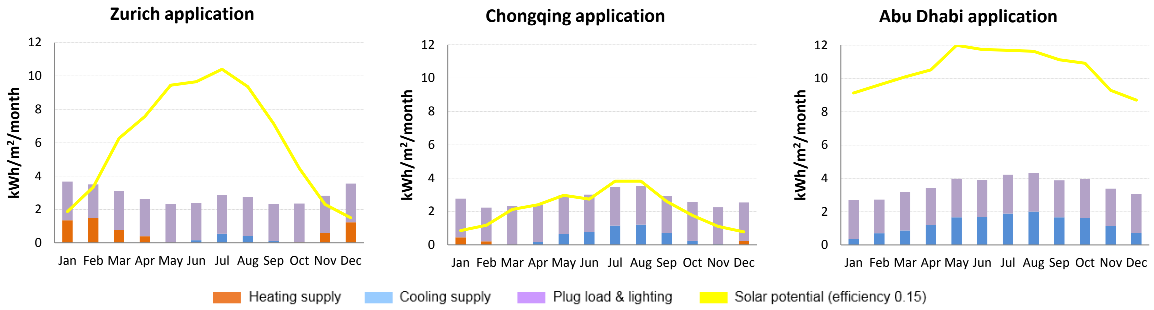


Fig.12 Monthly results for energy supply and solar PV potential (PV efficiency of 15%)

Overall, the results indicate that a relatively low energy demand performance can be achieved if the ‘Swiss’ standards are followed, and that the availability of solar energy to power the building has the potential to supply a major proportion of the energy for all three situations. However, in all situations some form of energy storage would be required for achieving zero carbon performance. In Abu Dhabi only short term ‘diurnal’ energy storage would be required for energy autonomy, whilst in Zurich longer term storage would also be needed to cover the winter months, when the monthly energy demand exceeds the solar availability. In Chongqing, the match between energy demand and solar potential is ‘borderline’ and there is not a net annual gain from the solar energy supply. It is interesting to note that for the reduced demand situation used in each location, the small power demand from lights and equipment now dominates the energy equation.

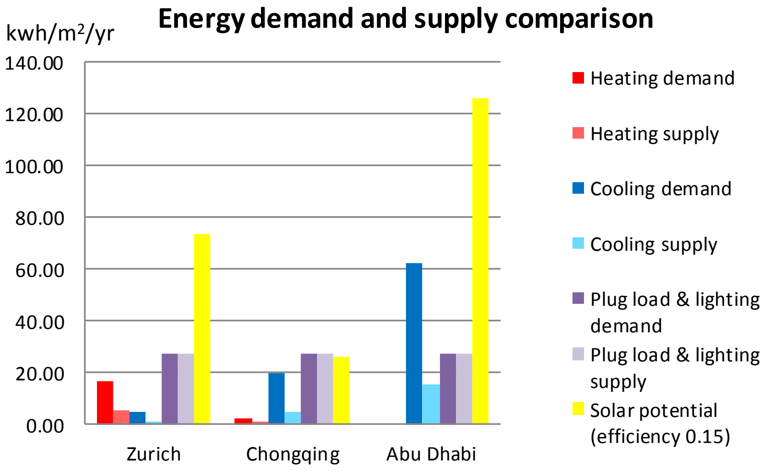


Fig.13 Summary of annual energy demand and the corresponding required supply accounting for heating and cooling system COP. The heating and small power use direct electric.

Fig. 14 shows the related carbon emission in the three locations, based on the local; carbon emission factors as presented in Table 3. Of course, if the energy supply is met by renewables the CO$_2$ emissions would be zero. The values are therefore related to the potential CO$_2$ savings as a result of providing renewable energy supply. It is interesting to note that due to the low CO$_2$ emission factor for Switzerland the potential CO$_2$ savings are relatively small. The implication is that low carbon design may be more important for countries with high carbon emission factors, resulting from high carbon grid supply.

Table 3 CO$_2$ emissions per kWh from electricity generation (IEA2013)

Location	Carbon dioxide emission factor (kgCO$_2$/kWh)
Zurich (Switzerland)	0.03
Chongqing (P.R. China)	0.76
Abu Dhabi (UAE)	0.6

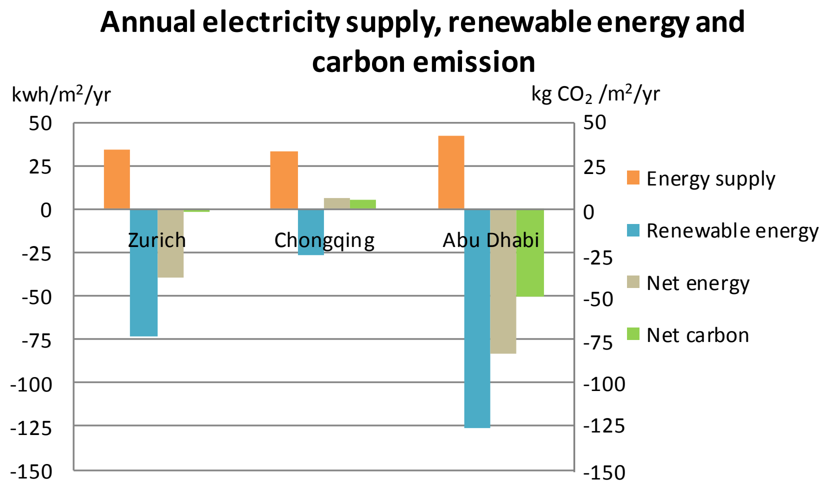


Fig.14 Summary of annual electricity supply, renewable energy and the related carbon dioxide emission savings

4. Conclusions

The paper has described a process of achieving low to zero energy design through a combination of reducing internal heat gains and façade design. Innovative cooling and heating systems, possibly using surface cooling and heating, combined with mechanical ventilation (as discussed in section 2.3), have the potential to maximize the benefits from reduced demand, although they have not been explicitly modeled in the simulations. They also result in other benefits, such as comfort and space use efficiencies. The paper has discussed the concept of a 'systems approach', combining reduced energy demand, with renewable energy supply and energy storage, and the use of building integrated renewable energy systems. The reported energy simulations have presented an analysis of the energy performance of the same building in three locations, relating energy demand to the required energy supply, and to the potential for meeting this supply from renewable energy (in this case solar PV). The results indicate that reducing energy demand provides the potential for using solar energy to meet all or most of the energy supply needs. Short term 'diurnal' storage may be sufficient for Abu Dhabi, whereas longer term storage may be needed for Zurich to achieve energy autonomy. In Chongqing the specific overcast climate features make the situation borderline.

A holistic systems approach to zero-carbon building design can therefore lead to reduced carbon emissions. The actual reduction in emissions will be related to the carbon content of the local grid as expressed through carbon emission factors. There are wide variations of carbon emission factors across the three locations, from 0.03kg/kWh in Zurich, to 0.76kg/kWh in Chongqing. The implication is that zero carbon design may be most beneficial in countries with a high carbon content supply grid.

There is also the potential for construction cost savings if an integrated ‘buildings as power stations’ approach is applied, using the renewable energy systems as construction elements, such as for the wall and roof, and offsetting increased fabric and renewable energy system costs with reduced system sizing for heating, cooling and ventilation. The relationship between energy costs and construction costs is a subject for further research.

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