Ecological design for climate mitigation in contemporary urban living

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Abstract: Evaporation is the most important hydrological function on Earth because it provides rain. As deforestation and urbanisation reduce plant cover and evapotranspiration, ever more short-wave solar radiation is converted to long-wave thermal emissions and sensible heat. Higher surface temperatures set up heat island effects, contributing to local, and ultimately, global climate change. Rainwater harvesting is therefore a key mitigation strategy against increased temperatures and drought. Urban water management can be enhanced by the ecological design of green roofs, evaporative facades, and ground infiltration measures, and in Berlin, several such projects are demonstrating these New Water Paradigm principles in action.

Keywords: urban heat islands; climate change; rainwater harvesting; evaporative cooling; green roof design; facades; new water paradigm.

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1 Introduction

Evaporation of water is the largest hydrologic process on Earth and also the most important component of energy conversion. Just as rainfall volume depends on the amount of water that has evaporated, so will a reduction in evaporation mean the increased conversion of short-wave global solar radiation to long-wave emissions and sensible heat. Additionally, a reduction in evapotranspiration on land – the combination of evaporation by surfaces and transpiration by plants – translates to a reduction in overall precipitation, effecting a further reduction in evapotranspiration, thus creating a 'snowball-effect' (Schmidt, 2009).

Global evaporation rates are being reduced in direct correlation with worldwide deforestation, sprawling urbanisation and the loss of fertile agricultural land (GTZ, 2007; Schmidt, 2010). Reduced evaporation rates cause higher surface temperatures and contribute greatly to the urban heat island effect. As such, rainwater-harvesting measures could play a key role as mitigation strategy against global warming. This approach would mean that rainwater management must focus on evaporation rather than discharge into sewer systems or infiltration.

The global change in hydrology and its impact on the climate requests a new water paradigm (Kravčík et al., 2007; www.waterparadigm.org). Until recently, evaporation has always been defined and understood as a ***loss***. In fact, evaporation is the very ***source*** of precipitation. Drought is conventionally expressed as a result of rising global temperatures, but if we take this new perspective then increased aridity is the cause, not the result, of the global warming. Intensive land-use patterns are causing the planet to dry out (Ripl et al., 2007; Kravčík et al., 2007).

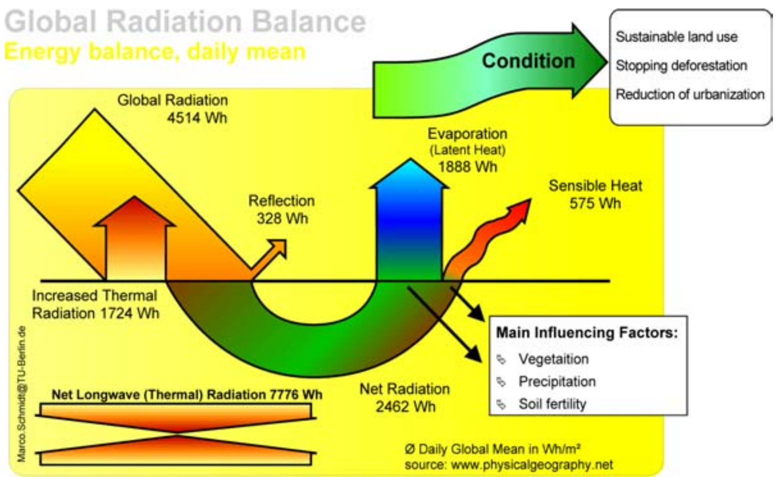
While we may all agree that global warming is caused by man-made activities, it is no longer acceptable to attribute this to the increase in greenhouse gas emissions. Rather, global changes in land use, in particular urbanisation, deforestation and desertification, are responsible for increased temperatures. The tremendous problems resulting from global climate and water issues are owing largely to unsustainable land use. In Germany, for example, urbanisation continues to grow at a rate of more than 1 km² daily (UBA, 2008). As a result of this urbanisation, an annual reduction of 200 mm evaporation releases sensible heat and thermal radiation of 50,000 GWh ($0.2\ m^3/a \times 680\ kWh \times 1\ Mio\ m^2 \times 365\ d$). Moreover, the associated loss of vegetation further impacts on hydrological processes, causing extreme storms, floods, drought and desertification.

A reduction in evapotranspiration leads to the conversion of short-wave global solar radiation into long-wave thermal emissions and sensible heat. All components by which global radiation is converted on the Earth's surface are illustrated in Figure 1, for a mean energy flux of 1 m^2 per day. Of this, 7.3% of incoming solar radiation is reflected, and 38% is directly converted to thermal radiation owing to the increase in surface temperatures. The total long-wave (thermal) radiation consists of atmospheric counter-radiation (7776 Wh/(m²d)) and the thermal radiation of the surface of the Earth (7776 + 1724 Wh/(m²d)). Compared with other available figures about the global mean energy budget (e.g., Trenberth et al., 2009), both components are presented separately in Figure 1. All surfaces above –273 C emit long-wave radiation, as they receive at the same time. Therefore, the long-wave energy gain and loss of the atmosphere, the atmospheric counter-radiation, must be considered separately from incoming short-wave global radiation.

Net radiation can be either converted into sensible heat (575 Wh/(m²d)) or consumed by evaporation, a conversion into latent heat. With 1888 Wh/(m²d), the energy conversion by evaporation is the most important component of all, even more than the thermal radiation converted from incoming short-wave radiation. Additionally, evaporation reduces the long-wave thermal radiation owing to the decrease in surface temperatures.

With regard to Figure 1, the entire global radiation balance is dominated by evaporation and condensation. Urbanisation results in a huge change to the small water cycle. Additionally, hard materials and surfaces in urban areas absorb and re-radiate solar irradiation and increase that area's heat capacity. Fundamentally, the main driving factors for the urban heat island effect are vegetation removal and paved surfaces (Figure 2(a) and (b)).

Figure 1 Global daily radiation balance as annual mean. Energy data based on www.physicalgeography.net



Impermeable surfaces like roofs and streets influence urban microclimates through a change in radiation components. As a result of changes in radiation, air temperatures inside buildings also rise and lead to discomfort or greater energy consumption by climate management (Schmidt, 2003). As an example of radiation changes in urban areas, Figure 3 illustrates the radiation balance of a black asphalt roof. Compared with Figure 1, most of the net radiation from the urban setting is converted to sensible heat rather than evaporation. Higher surface temperatures also increase the thermal radiation. Greening buildings is a logical solution to create more comfortable air temperatures in cities and to improve the microclimate around buildings. 'Green' in this sense means covered with vegetation, such that solar radiation is 'consumed' by evapotranspiration. Currently, the green building movement is focused mainly on energy consumption by heating, cooling and ventilation rather than on vegetation and evaporation. While the energy topic is a big concern, this is not directly linked with the problems of global warming and other environmental issues.

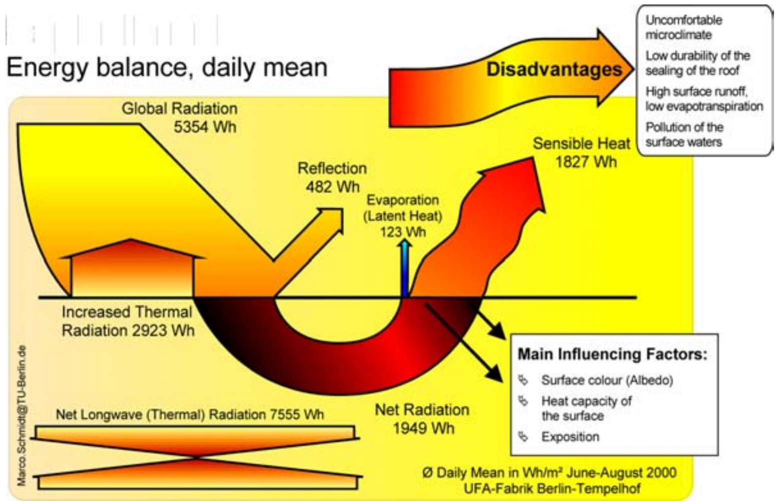
A cheap and reliable measure to create more comfortable air temperatures inside and outside of buildings is to green façades and roofs, thereby 'consuming' this energy by evapotranspiration. According to measurements taken at the UFA Fabrik in Berlin, a greened vegetated roof covered with 8 cm of soil transfer 58% of net incident radiation into evapotranspiration during the summer months (Figure 4). The annual average energy conversion of net radiation into evaporation is 81%, the resultant cooling-rates are 302 kWh/(m^{2}a) with a net radiation of 372 kWh/(m^{2}a) (Schmidt, 2005). The asphalt roof and the green roof in Figures 3 and 4 are monitored at the same location (Figure 5) in Berlin for the same period and are, therefore, directly comparable.

Figure 2 An urbanised landscape (Rio de Janeiro) in contrast to natural landscapes (Italy) significantly alter a region's patterns of radiation and hydrology

(a)

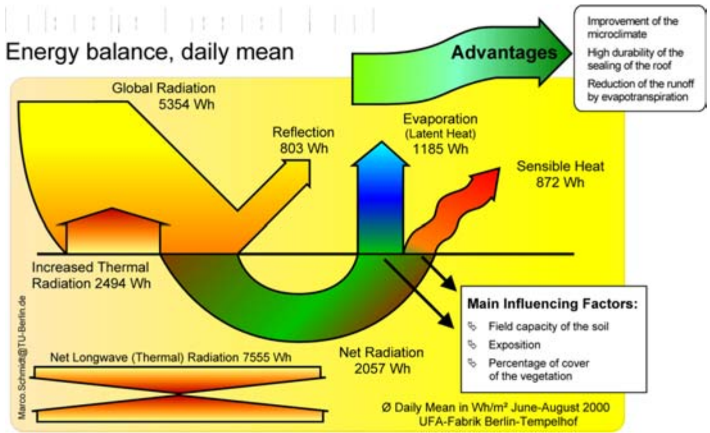
(b)

Figure 3 Radiation balance of a black asphalt roof as an example for urban radiation changes



Source: Schmidt (2005)

Figure 4 Extensive green roofs transfer 58% of net radiation into evapotranspiration during the summer months, UFA Fabrik in Berlin, Germany



Source: Schmidt (2005)

Figure 5 Greened roofs, UFA-Fabrik Berlin-Tempelhof (priority 2)

2 Best practice projects

With regard to the urban heat island effect and the issue of global warming, sustainable architecture and landscaping need to consider the natural water cycle, including evaporation, condensation and precipitation. In Table 1, water quality and other environmental issues are also considered as priorities and measures for sustainable urban development.

Table 1 Priority list of sustainable measures for urban areas regarding the mitigation of the urban heat island effect and global warming

Priority	*Value*		*Measure*
1	+ + +	1.0	Unpaved greened areas (parks, greened courtyards, street trees)
2	+ + O	0.78	Green roofs, green facades
3	+ +	0.67	Artificial urban lakes and open waters
4	+ OO	0.56	Rainwater harvesting (for cooling and irrigation)
5	+ O	0.44	Trough infiltration combined with large vegetated structures, grass pavers
6	+	0.33	Rainwater harvesting for toilet flushing and further utilisation
7	OO	0.22	Trough infiltration systems through natural soil, semi-permeable surfaces
8	O	0.11	Trench infiltration directly into the underground

The conventional principle of water discharge, which was implemented for over 100 years, nowadays bears disastrous environmental effects on surface water quality and on the climate. The paradigm shift, which must now be implemented at a local level, will require a complete rethinking of the existing urban planning and water management.

In Germany, rainwater infiltration has been a popular strategy in recent years. However, in spite of the great benefit of preventing negative impacts to surface waters, infiltration does not fully reflect the natural water cycle. Urban areas are not characterised by reduced infiltration rates (SenStadt, 2007), but rather the missing hydrological component is evaporation.

In the catchment area of Berlin/Brandenburg, about 80% of precipitation is converted to evaporation, while groundwater recharge and runoff together represent 20%. Urban areas are characterised by completely paved areas as well as semi-permeable surfaces with little to no vegetation. The semi-permeable surfaces allow much higher groundwater recharge compared with naturally vegetated areas (Schmidt et al., 2005), as they over-compensate for infiltration with reference to completely paved surfaces. Therefore, in the interest of effective environmental care taking, the provision for evaporation rather than infiltration needs to become a primary task.

Natural groundwater recharge in the Berlin region represents 10–20% of annual precipitation. Artificial infiltration systems manage an additional 6–10 times the surface of the infiltration area itself. This represents 500–900% of natural precipitation as runoff from paved areas, or about 40–50 times more than natural conditions. For example, a park area in Berlin receives 600 mm of precipitation annually. A grassy area without any artificial irrigation would typically evaporate about 500 mm into the atmosphere, while 100 mm serves for groundwater recharge, mainly in the winter season.

An infiltration system in the neighbourhood receives the same 600 mm of annual precipitation, plus an additional 4500 mm surface runoff from paved areas adjacent. Following the above-mentioned rates, these 5100 mm of water would be converted into about 700 mm evaporation, while 4400 mm represent groundwater recharge. This level of recharge is 44 times higher than the natural water cycle would permit (see Figure 6).

However, infiltration can also lead to evaporation provided that vegetation and vegetated structures are constructed in the neighbourhood. In such a case, infiltration systems must be supplemented with trees or façade greening systems. A discussion about the overcompensation of groundwater recharge by infiltration systems should not neglect the benefit of preventing rainwater from being discharged into sewers and surface waters. Nonetheless, impacts on the natural water cycle and on groundwater quality in urban areas must be expounded. For this reason, rainwater harvesting for toilet flushing gets a higher ranking in Table 1 compared with infiltration systems.

Figure 6 Trough infiltration system in Berlin, lacking vegetation (priority 7)

With a focus on rainwater harvesting and evaporation, in the past years four projects have been established in Berlin in cooperation with the 'Watergy' working group (Chair of Building Technology and Design) and the Chair of Applied Hydrology. All projects combine different measures of Table 1 to increase the efficiency of the water-related environmental benefits.

2.1 DCI Berlin, Potsdamer Platz

The DaimlerChrysler-Project at Potsdamer Platz in Berlin (from 1996 to 1998 the largest construction site in Europe) was built under very strict stormwater management regulations. To avoid overloading the existing combined sewerage system in Central Berlin, the building permit issued by city council stated that the new complex would drain runoff at a rate of no more than 3 l/sec/ha, or 1% of flows during storm events. To comply with this regulation, the Atelier Dreiseitl (www.dreiseitl.de) and landscape architect Daniel Roehr implemented the following techniques for the management of 23,000 m^3 precipitation that falls annually on this building site:

- extensive and intensive green roofs on all of the 19 buildings
- collection of roof-runoff for toilet flushing and plant irrigation
- an artificial lake for rainwater retention and evaporation.

Since infiltration was not possible at this site, the basis for the rainwater management concept involved rainwater harvesting for toilet flushing and evaporation by green roofs and an urban lake as a retention pond. Three cisterns providing 2550 m³ storage capacity correspond directly to 12% of the annual precipitation of the catchment area. The artificial lake, covering a total area of 13,000 m^2, can fluctuate its levels by 30 cm, which corresponds to an additional storage capacity of 11% of the annual precipitation (Figure 7). The water is cleaned and filtered through artificial filtering systems and additionally by a constructed wetland of 1900 m^2, which is planted mainly with *Phragmites*. The resulting water quality, as well as stormwater issues, has proven that this large rainwater system have performed very well for the last 10 years of operation.

Figure 7 Urban lake, supplied with roof-runoff at Potsdamer Platz (priority 3)

2.2 *Cultural Centre UFA-Fabrik in Berlin-Tempelhof*

The Cultural Centre UFA-Fabrik in Berlin-Tempelhof, home to various urban ecology projects (see www.ufafabrik.de), includes an integrated rainwater management project. As a first measure, most of the roofs were vegetated from 1983 to 1985 (Figure 5). In 1994, a rainwater-harvesting system was integrated. As a result, water from the green and conventional roofs is stored in a former underground waterworks station, along with runoff from street level.

The rainwater system at UFA-Fabrik has a total storage capacity of 240 m^3 in two cisterns. This is equivalent to 40 mm or 6.7% of annual precipitation of the catchment area. The system collects primarily ‘first flush’ stormwater. By capturing the pollutants and nutrients associated with the 'first flush', the UFA-Fabrik, which is situated on a separated sewer system, provides increased ecological benefits, by directing this polluted runoff to a modified constructed wetland for treatment. Collected rainwater is used to flush toilets and for irrigation. About 75% of rainwater used in the summer month is linked to irrigation. This rate of use, the large storage capacity for rainwater and the greened roofs represent the integration of best management practices for the new water paradigm.

2.3 Demonstration project 'Adlershof Physik'

The Institute of Physics in Berlin-Adlershof is located in a research and office facility featuring several measures of sustainable architecture. It was designed by the architects Georg Augustin and Ute Frank (Berlin) following an architectural competition held in 1997. Rainwater is used to supply a façade greening system and central air-conditioning systems with evaporative exhaust air cooling. The water is harvested from the roofs and stored in 5 cisterns.

Research elaborating on the performance of the building is funded by the Berlin Senate of Urban Development, Section *Ecological Construction*. The project includes permanent monitoring of the water consumption of different plant species and eight air-conditioning units. Continuous monitoring has been carried out since 2004.

The façade greening system (Figure 8) is evaluated to determine the importance of evapotranspiration and shading on the overall energy performance of the building, including temperature and radiation measurements. Data collected from this project is used to calibrate simulations that are designed to predict performance and benefits in range of different climatic conditions. This work will inform the design of future projects (SenStadt, 2010).

Figure 8 Façade greening system (priority 2)

About 280 parameters are electronically harvested every minute. Primary systematic evaluation is based on the water parameters and their relation to energy dissipation. Additionally, 12 plant species and their requirements for maintenance (fertilisation, plant protection) are monitored. Seven long-wave, short-wave and infrared sensors monitor the radiation concerning shading and reflection for each façade system. The building is not connected to stormwater sewers, reflecting one of the main goals of this decentralised system of rainwater retention and harvesting. Stormwater events from heavy rainfall are managed with an overflow into a small constructed pond in one of the courtyards, from which the water can evaporate or drain into the ground (Figure 9). To protect the quality of groundwater, this drainage is only allowed through surface areas covered with vegetation. Some of the roof surfaces are also extensively greened to assist in retaining and treating stormwater.

Figure 9 Artificial rainwater pond (priority 3) combined with trough infiltration for stormwater management (priority 7)

2.4 *Evaporative exhaust air cooling at the Institute of Physics*

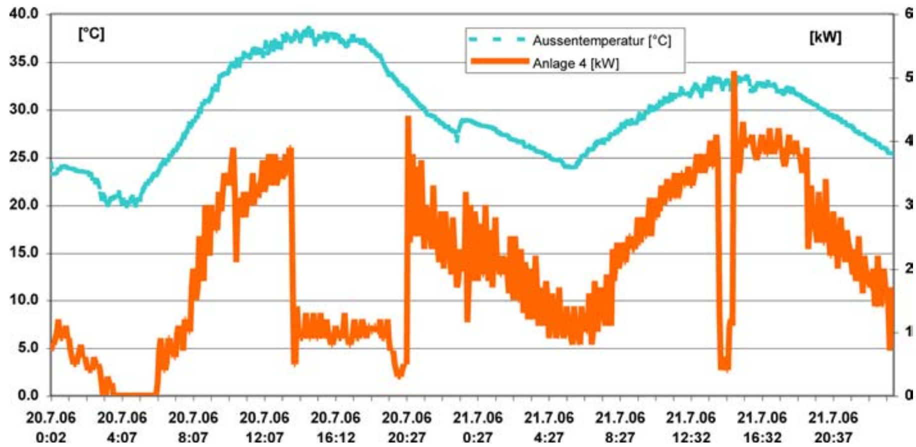
The German government's 'climate protection program' defines a target of reduction of fossil fuel consumption by 40% by the year 2020. This ambitious goal is mainly based on the reduction of energy consumption in the building sector. However, the growing use of air conditioning powered by electric energy is in direct conflict with this target. In contrast with the desired target, it is estimated that energy consumption for cooling and ventilation will increase by 260% by 2020 (EECCAC, 2003). Fortunately, a different approach to cooling, based on rainwater, can negate this conflict.

Air conditioning in the Institute of Physics is achieved through seven evaporative cooling units. These ventilation units use rainwater to cool air by the process of evaporation. First, rainwater is evaporated to reduce the temperature of the air leaving the building (Figure 10). This process has the capacity to cool exhaust air from 26–16°C. In a second step, fresh air entering the building is cooled as it passes across a heat exchanger with cooled air on its way out. This process is sufficient to maintain indoor temperatures of 21–22°C with outside temperatures of up to 30°C. When outside temperatures exceed 30°C, indoor temperatures are maintained with the additional aid of conventional cooling systems based on absorption chillers.

Figure 10 Adiabatic exhaust air cooling with rainwater in seven air-conditioning systems (priority 4)

Figure 11 demonstrates the results on performance of the systems studied. To evaluate the reduction in energy consumption, the evaporative cooling system was switched on and off. The resultant energy consumption of the conventional cooling system, in this case cold supplied by absorption chillers, indicates a decrease of 70%. The performance of 70% for the hottest day of the year suggests that the process is much more successful than expected. We can predict a reduction in energy consumption for cooling between 80% and 90% as an annual mean, compared with conventional systems. Additionally, the evaporation of (rain)water reduces the urban heat island effect, whereas conventional air-conditioning systems exacerbate the problem by consuming electric energy and releasing heat outside, influencing neighbouring buildings.

Figure 11 Evaluation of the reduction in energy consumption when switching the evaporative cooling system on and off



The advantage in using rainwater instead of tap water, which would also work, is that rainwater has no salt/no lime, therefore a low electrical conductivity. When using potable water, 2 m^3 are needed to evaporate 1 m^3 and concurrently produce 1 m^3 of sewage water. Using rainwater can conserve 50% in water volume and completely conserves wastewater.

Because of the evaporative heat loss of 680 kWh/m^3, even desalinisation by membrane reverse osmosis of seawater makes sense. The energy consumption of membrane seawater desalinisation decreased to a value of 7 kWh/m^3 in the past years. In this case, evaporation implies energy savings of 100 : 1! Conventional compression cooling systems consume 200–350 kWh compared with the benefit of evaporation of 1 m^3 of water. Heat release of conventional cooling systems in the streets outside the buildings is 680 kWh plus additional 200–350 kWh of electric energy consumption, which is converted into heat as well. Evaporative cooling simply consumes heat.

2.5 Façade greening system

Green façades were implemented at the Institute of Physics with two objectives:

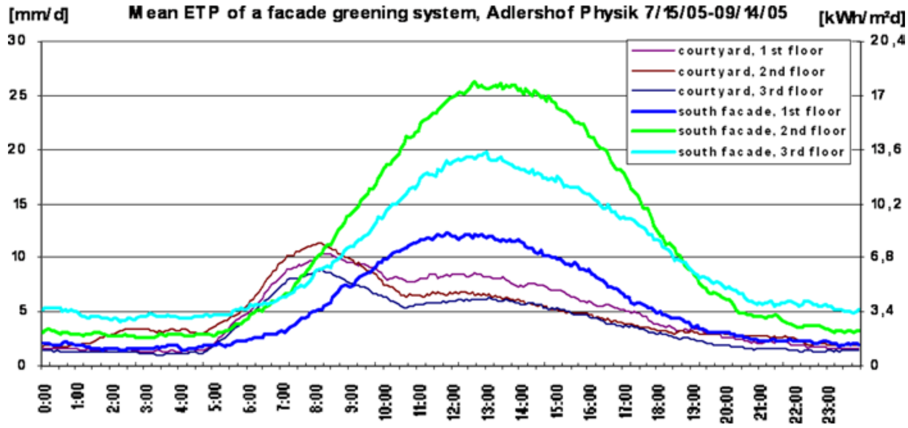
- to passively climatise the building through shading and solar radiation
- to harness evapotranspiration to improve the microclimate inside and around the building.

Plants provide shade during summer and, when defoliated in winter, the sun's radiation can lessen heating needs (Figure 8).

A total of 150 experimental troughs are organised in such a way that the water content is maintained at a constant level. Evapotranspiration demonstrates immediate feedback to water consumption. Since the troughs lack a facility to be weighed, evaporation is determined by measuring the water supplied to the trough throughout the day. Figure 12 shows the mean daily evapotranspiration of this façade greening system, measured as water consumption. The real ETP is extremely high, more likely because the plants have an optimised water supply and the surface area of the trough is small compared with the surface area of the plants. Mean evapotranspiration between July and September 2005 for the south face of the building was between 5.4 mm and 11.3 mm per day, depending on which floor the planters were located (Figure 12). This rate of evapotranspiration represents a mean cooling value of 157 kWh per day. Water consumption for the mature *Wisteria sinensis* increased up to 420 l per day for 56 of the planter boxes. This represents a cooling value of 280 kWh per day for one of the courtyards. The courtyard has a size of 717 m^2, the greened façade a surface of 862 m^2.

In selecting the climbing plants, emphasis was placed on choosing types that can grow in the extreme conditions of planter boxes. Of the various plants tested, *Wisteria sinensis* has proven to be the best. In addition to plants, a special system of irrigation and different substrates were also applied and studied. A factor in this selection was adequate capillary rise of water through the irrigation and substrate systems. Another aspect studied was providing of a layer of insulation to some of the planter boxes, to compensate for large shifts in temperature and especially to help protect against low winter temperatures. This comparison revealed that insulation can lead to significant differences in plant growth.

Figure 12 Mean evapotranspiration of the façade greening system in mm/day and correspondent cooling rates



The combination of providing shade in the summer and permitting solar energy gain in the winter supported a further design for a technological development: the implementation of simple translucent insulation system in arrangement with a vertical climbing plant structure. The overheating process of conventional translucent systems can be avoided, as evapotranspiration reduces the surface temperatures and improves the local microclimate. This system combines energy-saving strategies and provides the natural water cycle; therefore, it includes the '*old*' climate change discussion and '*future*' strategies on mitigating global warming.

2.6 Watergy

Watergy is a system for Water Treatment, Building Climate Control and Food Production. Watergy follows the development of a technology platform for the decentralised, basic supply of energy, water and food that can be used within a number of different applications (see www.watergy.de and www.cycler-support.net). The technological principle was proofed with two different prototypes between April 2003 and March 2006, and was funded by a European Union research project (NNE5-2001-683). In 2004, the first prototype was built for the purpose of greenhouse horticulture in Almeria, Spain. A second prototype was built in Berlin as a living and office building with an attached façade greenhouse.

The Watergy system combines solar collection with a mechanism for rainwater and greywater treatment. The building in Berlin (Figure 13) is based on the concepts of passive house insulation and solar-derived zero energy standards. A greenhouse located in front of a transparent wall on the southern face of the building acts as a modified double façade. The air inside the greenhouse becomes heated by solar gain and also humidified by the plants. The warm air rises to the ceiling, where it is further heated and further humidified within a secondary collector element. The upper side of this collector leads to a chilled air duct that is located inside the building. Thus, when the warm air cools off, it condenses and falls down through this duct, back into the greenhouse. Solar energy is stored in a 35 m^3 tank of water, enough for heating the building through the wintertime.

Figure 13 The Watergy prototype in Berlin-Dahlem (Germany), south-facing greenhouse façade

The prototypes are supplied with rainwater and a condensation unit to re-gain the evaporated water. The process of evaporation and condensation creates excellent water quality and shifts large amounts of energy, the previously mentioned 680 kWh/m^3. The evaporation of harvested rainwater inside of the greenhouse represents priority 4 of Table 1. The system can be implemented in landscapes where natural precipitation is not sufficient for crop production. In Almeria, the water demand for irrigation was reduced from 10 mm per day to 0.4 mm per day thanks to the recondensation of evaporated water in a cooling tower (Figure 14).

Figure 14 The Watergy prototype in Almeria (Spain), cooling tower in its centre (right)

3 Conclusions

Rainwater-harvesting measures, which focus on evaporation rather than infiltration, have tremendous potential to decrease the environmental impacts of urbanisation. On a global scale, the main cause of climate change is attributed to reduced evaporation

(Kravčík et al., 2007). With this knowledge, the popular focus on reducing greenhouse gas emissions to mitigate global warming may be a fatal misinterpretation of environmental processes. Indeed, simulations of global climate changes continue to neglect the fundamental driving forces of the global climate: transpiration by vegetation and evaporation by land. Thus, the correlation between CO_2 and global temperatures in fact represents the processes of vegetation, namely photosynthesis and evapotranspiration.

Through design strategies such as green facades, green roofs and permeable ground surfaces, rainwater-harvesting measures can play a key supportive role as adaptation and mitigation strategies against the urban heat island effect and global warming. When considering a close-up of the small water cycle, we entertain the emergence of a new water paradigm (compare www.waterparadigm.org). As part of this new paradigm, harvesting rainwater for evaporation would become a first priority in urban areas: not a single drop of water may leave urban surfaces simply to be funnelled into sewer systems. Rather, harvested rainwater can be used for evaporative cooling via vegetation or air-conditioning units.

The research summarised earlier shows that evaporation of water is the cheapest and most effective way to cool a building. It is known that 1 m^3 of evaporated water consumes 680 kWh of heat. Thus, instead of conventional cooling systems (old cooling approach), which release heat outside the building, produce additional heat and consume mainly non-renewable energy, the evaporation of water simply consumes heat (new cooling paradigm). In this way, energy is released when water vapour condenses on any given surface, or in the atmosphere. Condensation in the form of clouds in the atmosphere represents the primary heat/energy loss by the Earth into space.

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