
Taylor & Francis
Taylor & Francis Group

Architectural Science Review

ISSN: 0003-8628 (Print) 1758-9622 (Online) Journal homepage: http://www.tandfonline.com/loi/tasr20

# Applying biomimicry to design building envelopes that lower energy consumption in a hot-humid climate

**Daphne Fecheyr-Lippens & Pravin Bhiwapurkar**

ARCHITECTURAL SCIENCE REVIEW, 2017
VOL. 60, NO. 5, 360–370
https://doi.org/10.1080/00038628.2017.1359145



# Applying biomimicry to design building envelopes that lower energy consumption in a hot-humid climate

Daphne Fecheyr-Lippens [a*] and Pravin Bhiwapurkar [b]

[a]Department of Biology, University of Akron, Akron, OH, USA; [b]School of Architecture and Interior Design, University of Cincinnati, Cincinnati, OH, USA

**ABSTRACT**
Design thinking in architecture has shifted due to warming climate, and the role it plays in energy consumption. The building envelope is a key design element, as it mediates the maintenance of comfortable indoor temperatures. Our study uses the solution-based approach for generating biomimetic architectural concepts described by Badarnah, Lidia, and Usama Kadri [2014. "A Methodology for the Generation of Biomimetic Design Concepts." *Architectural Science Review* (June): 1–14. doi:10.1080/00038628.2014.922458]. Our proposed biomimetic design was inspired by the adaptive strategies of the African reed frog and the Hercules beetle. It incorporates a hydrogel chamber, embedded phase changing material, and the use of adaptive thermal comfort. We calculated potential summertime energy savings for a small-sized office building in Chicago using DesignBuilder/EnergyPlus. Our results show a potential of up to 66% reduction in the space conditioning energy use intensity mainly thanks to a decrease in cooling energy needs.

**ARTICLE HISTORY**
Received 7 April 2017
Accepted 20 July 2017

**KEYWORDS**
Biomimicry; architecture; building envelope; adaptive thermal comfort; thermoregulation; energy simulation



## 1. Introduction

Scientific evidence and greater awareness about climate change and environmental pollution have influenced architectural design in the twenty-first century. Architecture plays a crucial role; buildings worldwide use 20–40% of total consumed energy, largely through heating and cooling building interiors. Heating, ventilation and air conditioning (HVAC) systems account for 48–57% of total energy consumption depending upon geography (U.S. Energy Information Administration (eia) 2013) and when lighting is also considered this number rises above 65% (CBECS 2012). Warming urban climates and increasing frequency of extreme heat events are expected to have a significant impact on future energy consumption (Huang and Gurney 2016). The building envelope is the most important structural subsystem affecting the energy balance of the building (Schittich, Lang, and Krippner 2006), and is therefore an ideal element to optimize for improved thermal behaviour.

The building envelope is usually a static barrier between exterior environmental variables and dynamic inside activities. A new architectural trend is to make an adaptive envelope that is responsive to both exterior and interior variable environments (Armstrong 2012). The ability to adapt to conditions is relatively new to the field of architecture, whereas it is a phenomenon as old as life itself. Living organisms are able to adapt to changing weather conditions while maintaining their body temperature in very narrow ranges, because they implement physiological, morphological and/or behavioural means for thermoregulation (Badarnah 2015). In this context, biomimicry (i.e. the emulation of biological strategies) has a huge potential as a design tool to improve the sustainable performance of buildings.

In 1997, Janine Benyus popularized biomimicry as an emerging discipline that mimics nature's forms, functions, processes and systems to create a healthier, more sustainable planet (1997). The use of biomimicry as a design approach to specifically redesign building envelopes has recently become more prevalent (Badarnah Kadri 2012; Gostonyi 2013; Mazzoleni 2013; López et al. 2017). For example, studying the mechanism of how plant stomata function in relation to gas exchange resulted in building envelopes adaptive to varying environmental conditions (López et al. 2015). The banana slug inspired the design of a greenhouse with an adaptive envelope that adjusts and changes according to weather conditions, and collects rain water to irrigate the plants, with overflow stored for further irrigation (Mazzoleni 2013).

However, copying nature does not necessarily result in more sustainable solutions (Reap, Baumeister, and Bras 2005). It is therefore important to consider different levels of emulation: form, process and ecosystem (Benyus 1997). Mimicking natural strategies in buildings can occur at many levels. For example, you could simply create a building that only mimics form for aesthetics (e.g. Tirau's iconic dog building in New Zealand) or one that mimics a natural form to provide

**CONTACT** Pravin Bhiwapurkar pbhiwapurkar@gmail.com School of Architecture and Interior Design, University of Cincinnati, Cincinnati, OH45220, USA
*Co-first authors: D. F. L. contributed to the biomimicry part, whereas P. B. contributed to the architectural engineering and simulations. Both authors contributed towards synergy of biomimicry and design applications.

additional functionality (e.g. the glass panels of the Waterloo International Terminal mimic the flexible scale arrangement of pangolin, which allows the building to respond to changes in air pressure when trains are entering and departing from the terminal) (Zari 2010). In addition to mimicking form, it is also important to consider the manufacturing process – nature often uses self-assembly and readily available materials (Benyus 1997; Whitesides and Grzybowski 2002). For increasing the likelihood of sustainable outcomes, the ecosystem level should also be taken into account by considering how a building will function in a particular habitat and integrate with the already existing urban system (Weissburg 2016; Zari 2017). Using biomimicry for creating more sustainable designs requires a thoughtful practice and an interdisciplinary approach from the onset (Kennedy et al. 2015). The development of methodological tools to support a biomimicry approach for energy-efficient building design provides a framework for biomimicry's successful implementation (Badarnah and Kadri 2014; Chayaamor-Heil and Hannachi-Belkadi 2017). Badarnah and Kadri (2014) provide a systemic review on different biomimicry methodologies. Currently, two different approaches have been recognized: either starting from a design challenge [i.e. *top-down* (Speck and Speck 2008), *challenge-to-biology* (Baumeister 2014), *biomimetics by analogy* (Gebeshuber and Drack 2008), *problem-based* (Vattam, Helms, and Goel 2009)] or starting from an inspiring biological observation [i.e. *bottom-up* (Speck and Speck 2008), *biology-to-design* (Baumeister 2014), *biomimetics by induction* (Gebeshuber and Drack 2008), *solution-based* (Vattam, Helms, and Goel 2009)].

This paper focuses on how energy needs of a building can be reduced using biomimicry principles. We investigated if the solution-based approach described in Badarnah and Kadri (2014) can be used to redesign a building envelope that effectively lowers energy consumption while meeting thermoregulatory needs. We will describe our design process in detail, but practically we examined the Hercules beetle (*Dynastes hercules*) and the African reed frog (*Hyperolius viridiflavus nitidulus*) as natural models and mimicked their unique biological mechanisms to design a biomimetic building envelope that lowers energy consumption while minimizing energy needs for thermoregulation. Although a biomimetic architectural design is supposedly more responsive to the external and interior environment by design, we introduced a simulation tool that allows the evaluation of its energy performance in a chosen climatic context (Fernández Cadenas and Neila Gonzalez 2015). Moreover, this allowed us to investigate the importance of each of the different biomimetic design components.

## 2. Methods

The biomimicry methodology used in this paper (Table 1) is based on the solution-based approach for generating biomimetic architectural concepts described in Badarnah and Kadri (2014), which has been adapted from the fundamental work on Biomimicry Thinking by Baumeister (2014) and the top-down approach developed by the Plants Biomechanics Group led by Thomas Speck (Speck and Speck 2008). The reason we chose to follow this approach is because we wanted to ground ourselves quickly into the solution space and did not want to restrict our design process to one specific problem. We started with inspiring observations from nature, and focused on the challenges of heat and humidity prevailing in hot-humid conditions to help us identify adaptive biological systems in nature. The two most inspiring examples were the African reed frog and the Hercules beetle because of their adaptive responses to extreme heat and humidity, respectively. It was important to obtain a proper understanding of the biological strategies before we could use them as inspiration in the next phases. To further understand their unique adaptive mechanisms, we used the AskNature.org database and Google Scholar's search engine to find scientific research papers. Then we explored how these biological strategies could be applied to design an innovative building envelope that lowers energy consumption. We first investigated the thermal behaviour of a prototypical building found in the U.S. to obtain a better understanding of the context of the biomimetic design and this assisted us to abstract the biological strategies into more suitable and applicable design principles. We focused on Chicago because it is considered to have a hot and humid climate, and thus accompanied with intensive HVAC usage. To evaluate our biomimetic design, we performed comparative energy simulations to determine if the biomimetic building envelope indeed saved energy and which of the different biomimetic design components is most important for achieving this.

### 2.1. Biological domain

#### 2.1.1. The African reed frog

The first biological example which inspired us was *H. viridiflavus nitidulus*, a species of the African reed frog that lives in the savannahs of western Africa (Lampert 2001). While most savannah frogs hide themselves under sand to escape high temperatures and low air humidity, immature individuals of African reed frog survive the very hot, dry season while fully exposed to the sun and harsh conditions clinging to vegetation. They are

**Table 1.** Solution-based biomimicry methodology adapted from Badarnah and Kadri (2014).

| | Strategies | African reed frog | Hercules beetle |
|---|---|---|---|
| Biological domain | • Identify biological system<br>• Analyse biological system<br>• Understand biological principles | • African reed frog<br>• Behavioural and morphological changes<br>• Light reflection and thermal adaptation | • Hercules beetle<br>• Cuticle, porous photonic crystal<br>• Humidity-based colour change |
| Transfer phase | • Understand thermal behaviour of building<br>• Abstract and brainstorm | • High-albedo surface<br>• Adaptive thermal comfort model<br>• Delay internal heat gain | • Passive (de)humidification<br>• Superabsorbent polymers |
| Technological domain | Implement technology through prototyping and testing | Design and evaluate energy savings of biomimetic envelope system using energy simulation | |

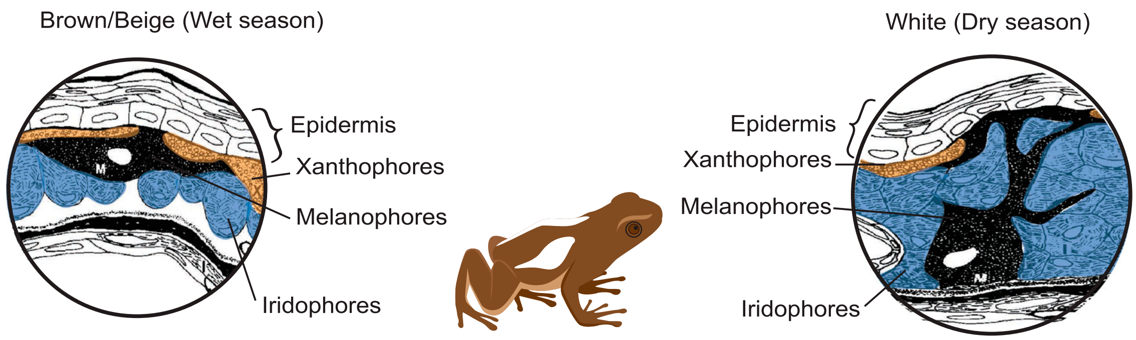


**Figure 1.** Comparison of the skin of the African reed frog during wet and dry season. The skin contains three types of chromatophores: iridophores (blue), xanthophores (orange), and melanophores (black). The number of iridophores increases significantly during transitioning to the dry season, while the xanthophores and melanophores are shifted to the bottom. Adapted from Kobelt & Linsenmair (1986).

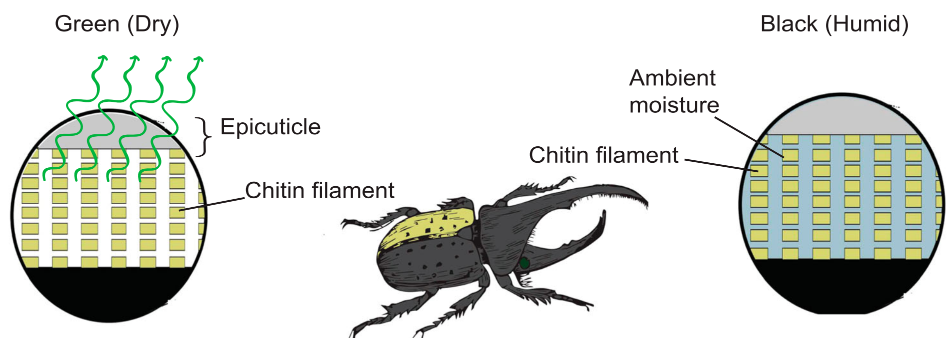


**Figure 2.** Color changing mechanism in the Hercules beetle. A spongy layer of filamentary strings of chitin are arranged in layers parallel to the epicuticle, creating open pores that are filled with air (dry environment) or water (humid environment). Depending on the contrast between the refractive indices this results in a greenish (dry) or black (humid) color.



highly dependent on water and staying above ground permits them to catch even the smallest amount of rain or condensation of water (Geise and Linsenmair 1986; Lampert and Linsenmair 2002). They hold a special sitting position to minimize water loss, minimize solar exposure and move only when seriously disturbed.

The African reed frog can survive in harsh dry and hot conditions, thanks to its spectacular physiological adaptations triggered when temperatures reach 36–38°C. Their unique aestivation behaviour lowers their metabolic rate at high temperatures and arid conditions. Their body colour changes from beige or grey to a highly reflective white (Kobelt and Linsenmair 1986). During aestivation, the frog does not urinate or defecate, holding all nitrogenous waste stored in its body. Yet, high concentrations of urea in body fluids can be dangerous due to osmotic problems; the frog solves this by converting its nitrogenous waste into purine crystals which it stores in specialized cells called iridophores (Schmuck, Kobelt, and Linsenmair 1988). The number of iridophores increases four to six times during the dry season forming a layer on the upper part of the skin (Figure 1). Because these purine crystals create a high refractive index contrast to the surrounding cytoplasm, the iridophores become light-reflecting cells (Levy-Lior et al. 2008, 2010). Their position during the dry season is almost parallel to the skin surface, causing them to act as a light reflector similar to a mirror (Kobelt and Linsenmair 1992). Interestingly, the frog has two other types of specialized cells, chromatophores, which contain certain pigments (Kobelt and Linsenmair 1986). During the wet season, the upper part of the skin will consist mainly of xanthophores (creating yellowish colours) and melanophores (creating brown/black) resulting in a beige or grey colour (Figure 1). The number of xanthophores and melanophores does not increase during transitioning to the dry skin. However, they are shifted to the bottom of the skin and are replaced by layers of iridophores, which results in a highly reflective white coloration.

### *2.1.2. The Hercules beetle*

A second organism we have chosen for this study is the Hercules beetle (*Dynastes hercules*). Hercules beetles can be found in the rainforest of South and Central America (Rassart et al. 2008). They are one of the largest beetles in the world and can grow up to 17 cm in length. Being primarily nocturnal makes them particularly vulnerable to predators. Consequently, they have found a way to adapt their body colour to match that of its environment and be less conspicuous. The beetle's body changes from black on a dark, rainy day or night to an olive-greenish colour during sunny days (Figure 2). This colour change is reversible, does not need external energy, and happens within mere minutes.

The greenish coloration under dry conditions originates from a spongy layer underneath the transparent epicuticle that has a 3D photonic crystal structure (Figure 2). Specifically, a network of filamentary strings of chitin are arranged in layers parallel to the cuticle surface, creating open pores that are filled with air (Rassart et al. 2008). Because the photonic crystal structure (refractive index $n = 1.36$) and air ($n = 1.00$) have a high refractive index contrast, this causes multi-layer interference (Sun, Bhushan, and Tong 2013) resulting in a greenish colour. On humid days, the spongy layer absorbs ambient moisture. Water ($n = 1.33$) has a very similar refractive index from the surrounding chitin so there is no light reflection, which makes the body appear black.

## 2.2. Transfer phase

Having an understanding of the biological systems allows for applicable abstraction into design principles that can be used for brainstorming and solution thinking to design biomimetic building envelopes. To realize transferability of relevant design principles to buildings, we first needed to understand how a building behaves as that ultimately determines the context of a successful biomimetic design. We investigated the thermal behaviour of a small office building as a test case using a whole building simulation program, DesignBuilder4.5/EnergyPlus 8.1 (DesignBuilder Software Ltd, n.d.). This building type was selected because it accounts for significant building efforts in the U.S. and consumes significant amounts of energy (Thornton et al. 2010).

### 2.2.1. Simulation parameters

A representative three-storied, small-sized office building of 1366 $m^2$ (CBECS 2012) was modelled per ASHRAE Standard 90.1 Climatic Zone:5A (ASHRAE 2013) and Appendix G requirements (standard 90.1 requirements for energy efficient buildings). This building type represents a majority of the built-up area in the U.S. and therefore it is selected for this investigation. Chicago (IL) was chosen as a suitable test location because it poses heat- and humidity-related challenges (ASHRAE 2013) during summer months, thus being a good case study model to demonstrate energy saving potential of our selected biological inspirations.

The square shaped building footprint of 21.3 × 21.3 m was chosen for orientation neutrality and based on the existing building stock in the U.S. (Thornton et al. 2010). The perimeter and core-zoning pattern was adopted for understanding thermal behaviour of the building because it accounts for heat exchanges on differently oriented building facades. Each floor has four thermal zones along the perimeter (depth is 3.65 m, adopted from Thornton et al. 2010) and one core zone (Figure 3). The summertime temperatures of the cross-section of the baseline envelope were taken from a previous study (Bhiwapurkar and Moschandreas 2010). The floor to floor glazing of 30% is equally distributed on exteriors walls and its thermal properties (i.e. solar heat gain coefficient, *U*-value and visible transparency) are kept constant at 30% throughout this study.

The selected envelope construction is based on common practices adopted for small-sized office buildings in the U.S. (Richman et al. 2008; CBECS 2012) and the interior space is air-conditioned by a packaged single zone DX system with furnace (System3: PSZ-AC). The HVAC system maintains a 23.8°C cooling set-point and 21.1°C heating set-point during occupied hours. During off hours, thermostat set-points are 27.7°C for cooling and 17.7°C for heating. The economizer is set to a maximum dry bulb temperature of 21.1°C. The operating schedule is from 8:00 am to 5:00 pm. Additional details on simulation parameters are published elsewhere (Bhiwapurkar 2015).

### 2.2.2. Thermal behaviour of building

The building's thermal behaviour is determined by an addition or extraction of heat from various thermal zones to maintain the temperature set-point range 21.1–23.8°C. The building envelope is in constant flux with outside and inside environmental conditions, which influences the building's thermal behaviour. Solar heat, the primary source of external heat, is transferred inside the building via the envelope – through glazing, walls and the roof. Thermal properties of these elements determine the heat flow, thus making material choices and its organization in the construction assembly important. Buildings also gain heat from internal sources: electric lighting, equipment and people, affected by the building's operating schedule for lighting, equipment and HVAC, based on occupancy.

Figure 4 presents the thermal behaviour of the middle floor of a three-storied building based on the amount of heat extracted to maintain the desired thermal comfort range (i.e. heat extraction rate). We chose the middle floor because it is less affected by the roof and ground, which allows us to focus on the building envelope. Time of day, solar position and the intensity of radiation play a significant role in the thermal behaviour of the building. The core zone receives heat primarily generated by internal sources while the perimeter zones have a significant external heat load. For example, the East zone receives

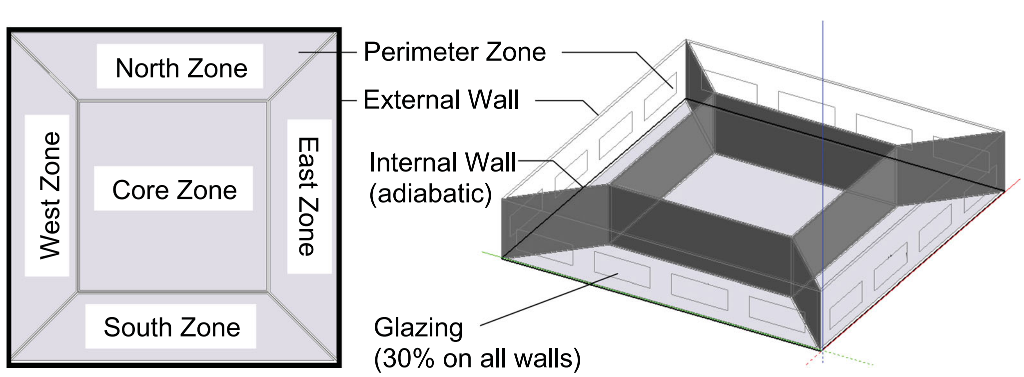


**Figure 3.** Thermal zoning: plan and axonometric view. Each floor has four perimeter zones and one core zone.

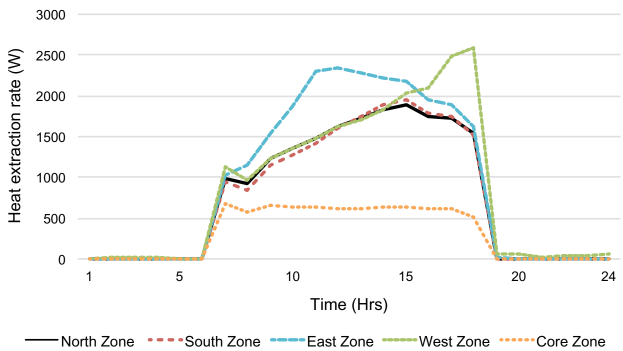


**Figure 4.** Heat extraction rate from thermal zones of the middle floor on the hottest day of the year (July 26).

early solar radiation, warms up quickly and the heat extraction rate peaks as early as at 11:00 am, reaching 2350 W. In contrast, the West zone starts receiving solar radiation after noon and its heat extraction rate peaks at 4:00 pm, reaching 2587 W. The Core zone is not exposed to outside conditions and is surrounded by adiabatic internal walls (does not allow heat exchange between zones), keeping the heat extraction rate peak to approximately 600 W.

Further investigation of the building envelope shows that when the heat extraction rate peaks, the external wall surface temperature can be up to 27.7°C higher than the outdoor air temperature. In contrast, the internal wall temperature is closer to the room temperature because of indoor thermal conditions. The difference between external and internal wall temperature ($\Delta T$) determines the amount as well as the direction of heat transfer (i.e. from higher to lower temperature).

### 2.2.3. Abstracted design principles

Our investigation of the thermal behaviour of the building showed that the high heat extraction rate due to the transfer of heat from outside to inside is a key factor contributing to high cooling energy needs. Therefore, this became the challenge area for which to focus our biomimetic solutions (as well as the design principles abstracted from the biology). Having a better problem definition and design focus allowed us to abstract the biological principles in a more suitable and applicable fashion.

For the African reed frog, we found the trigger of physiological adaptations according to body temperature to become highly reflective particularly interesting as a strategy to survive the very hot conditions. This inspired us to use a high albedo material to reflect solar radiation and use the indoor temperature to trigger adaptive thermal comfort (ASHRAE 2004) to minimize cooling energy needs (de Dear and Brager 2001). The adaptive thermal comfort model goes beyond fundamental physics and physiology to determine the range of comfortable inside temperatures, by also including contextual effects such as the physiological responses of building occupants (de Dear and Brager 2001; Brager, Zhang, and Arens 2015). There is empirical evidence of increasing occupants' satisfaction at the work place with wider temperature ranges (Brager, Zhang, and Arens 2015). Using an adaptive thermal comfort model, the comfort temperature range in this study has been extended from a narrow 21.1–23.8°C based on the conventional thermal comfort zone to a wider 21.1–31.7°C by allowing ventilation when it is comfortable outside (Bhiwapurkar 2016).

The physiological adaptations in response to high body temperature of the African reed frog inspired us to think about internal heat gain. An additional design component that we used for delaying the internal heat build-up is embedding phase change materials (PCM). These materials melt and solidify at a certain temperature and therefore are capable of storing and releasing large amounts of energy. They have been recently introduced for architectural purposes because they can be used for latent heat storage and delay the peak thermal load (Sharma et al. 2009; Kośny, Shukla, and Fallahi 2013). In this study, we chose commercially available Bio-PCM made from rapidly renewable and sustainably harvested non-food natural materials like palm oil by-products, coconut or soy (Phase Change Energy Solutions 2005).

In summary, the African reed frog inspired us to develop a biomimetic building envelope that minimize the heat extraction rate by reflecting solar radiation, using adaptive thermal comfort and increasing thermal delay.

The biological principle of the Hercules beetle was abstracted into: 'leverage ambient humidity to passively and reversibly absorb water'. Inspired by this strategy, we used a passive reversible dehumidification process that helps support the adaptive thermal comfort in the building. During hot, humid summer conditions, dehumidification improves thermal comfort by removing latent heat via evaporative process (Badarnah 2015). We chose to use superabsorbent polymers (i.e. hydrogels) for this application as they mimic the mechanism of the Hercules beetle. Superabsorbent polymers can absorb and retain extremely large amounts of liquid relative to their own mass without becoming soft or disintegrating (Zohuriaan-Mehr and Kabiri 2008). Hydrogels are superabsorbent polymers that absorb water via hydrogen bonding.

## 2.3. Technological domain: designing the biomimetic building envelope

The proposed biomimetic building envelope composed of an adaptive thermal comfort approach, a high albedo surface, and an integrated hydrogel and Bio-PCM system, is illustrated in Figure 5. The biomimetic envelope has three main components and is designed to fit into a common curtain wall system. The first component is a standard glazing and high albedo solid panel system that covers the majority of the façade. The second component is a series of hydrogel dehumidification chambers. The third is a wall integrated with a Bio-PCM layer to remove undesired heat from the air. The integration with an HVAC system is useful in case additional cooling or humidification is required before circulating the air in the building.

The biomimetic building envelope is designed to save energy by preconditioning outside air in a four-step process (Figure 5) while achieving adaptive thermal comfort conditions inside. First, outside air (1) is drawn through a filter and into the hydrogel chambers. As the air passes over the hydrogel (2), the moisture is absorbed, which will increase the temperature of the dried air. Next, the dehumidified and relatively hot, dry air (3) moves over the encapsulated Bio-PCM, which absorbs sensible heat. The air is cooled and the absorbed heat can be used to preheat

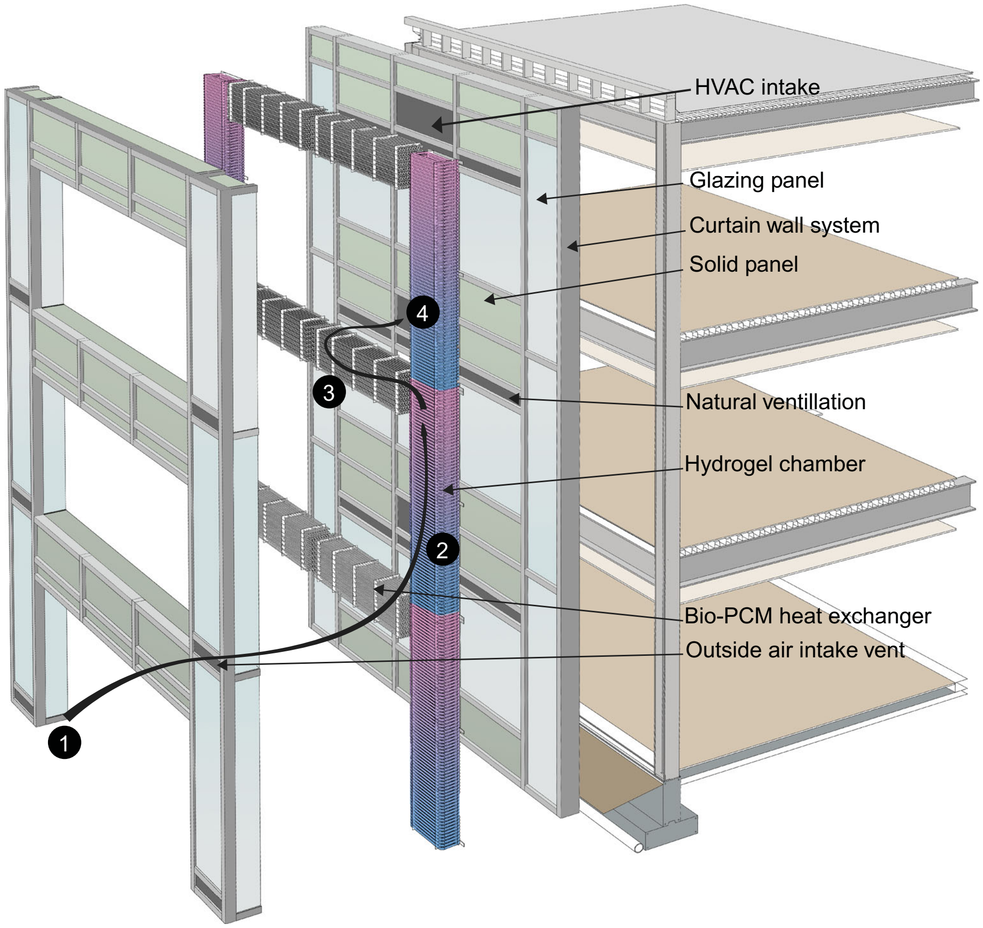


**Figure 5.** Graphic showing the main components of the biomimetic building envelope. Hot humid outside air (1) is dehumidified in the hydrogel chambers (2) and it is cooled by heat exchangers (Bio-PCM encapsulated wall) (3) The preconditioned air is then used for natural ventilation or circulated via an integrated HVAC system (4).

water entering a domestic hot water boiler (note, this design aspect goes beyond the scope of this paper, and was therefore not included in the study). The pre-conditioned air can be used for natural ventilation (NV) or if needed, conditioned further by the HVAC system (4). Based on the air movement through the building envelope system, it is possible to create a mixed-mode (MM) and NV scenario in the building (de Dear and Brager 2002; Brager, Zhang, and Arens 2015). Such variations are explained in the following section. By reducing the dehumidification and cooling loads of the HVAC system, the overall energy use of the building can be greatly reduced.

## 3. Evaluating energy saving potential of our biomimetic building envelope

Four variations of the biomimetic building envelope system were investigated for energy saving potential in comparison to the baseline envelope system (Table 2). These variations included modification in the existing building envelope system to achieve adaptive thermal comfort using MM ventilation and NV, and its combination with the integrated Bio-PCM layer.

### *3.1. Baseline building envelope*

The baseline building envelope (Table 2) is represented by a dry wall with stucco and board insulation on exterior side (R13 + R10ci), whereas the metal deck roof has insulation above (R30ci) that meets the code requirements (see Section 2.2.1). The thermal properties of glazing include a solar heat gain coefficient of 0.4, a *U*-value of 2.38 W/m$^2$K, and a visible transparency of 1. The baseline building with HVAC system maintains 21.1–23.8°C and it is mechanically ventilated using constant air volume during the occupied period. The mechanical ventilation indicates that the outside air and/or re-circulated air is delivered to the thermal zone. In this study, the mechanical ventilation delivers air through a centrally ducted air conditioning system. Simulations were performed using 'room ventilation' where mechanical ventilation is modelled using EnergyPlusZoneVentilation:DesignFlowRate data separate from the main HVAC system.

### *3.2. Biomimetic building envelope using MM ventilation*

The biomimetic building envelope using MM ventilation uses mechanical ventilation and allows NV when it is desirable outside while keeping heating and cooling set-points similar to the baseline, that is, 21.1–23.8°C (see Bhiwapurkar 2016). NV is made possible with mechanically controlled windows. Outside air requirement data is set at the zone level and is a sum of mechanical ventilation, NV and infiltration in air changes per hour (ac/h). This data can be used for checking occupant discomfort when used together with other environmental elements like

**Table 2.** Comparison of the baseline prototypical small office building envelope with the proposed variations of the biomimetic building envelope system.

| Biomimetic envelope component (Figure 5) | Baseline[a] | MM ventilation | NV | PCM with MM and NV |
|---|---|---|---|---|
| 1 | Outside air is conditioned by the roof top unit and circulated via central duct system | Outside air (21.1–23.8°C) passes through the dehumidification zone | Outside air (21.1–31.7°C) passes through the dehumidification zone | Outside air (temperature crf. respective scenario) passes through the dehumidification zone |
| 2 | | Dehumidification zone (moisture is absorbed by the hydrogel) | Dehumidification zone (moisture is absorbed by the hydrogel) | Dehumidification zone (moisture is absorbed by the hydrogel) |
| 3 | | | | Heat exchanger (sensible heat stored by Bio-PCM) |
| 4 | | Fan Coil Unit (FCU) to treat and circulate air per indoor thermal comfort conditions (21.1–23.8°C, 0.3 ac/h) | Air is circulated naturally in indoor spaces, fan assistance is available to achieve minimum air changes, FCU to treat and circulate air per indoor thermal comfort conditions (21.1–31.7°C, 0.3 ac/h) | Air is circulated naturally in indoor spaces, fan assistance is available to achieve minimum air changes, FCU to treat and circulate air per outside indoor thermal comfort conditions (21.1–31.7°C, 0.3 ac/h) |

[a]Does not incorporate any of the biomimetic building envelope components presented in Figure 5.



air temperature and humidity. The required air changes per hour (0.3 ac/h) at minimum velocity (0.001524 m/s) in an MM cooling allow occupants to adapt to the relatively higher temperatures and humidity in the office building because the provision of operable (manual or mechanical) windows and the perception of fresh air improves perceived comfort (Brager and Baker 2009).

### 3.3. Biomimetic building envelope using NV

The biomimetic building envelope using NV is made possible by extending the set-points, particularly for cooling, that is, from 21.1–23.8°C to 21.1–31.7°C. Adjusting the cooling set-point to 31.7°C allows the adaptable thermal comfort to be maintained by NV only. The mechanical system will only be activated to heat and cool if temperatures do not fall between the set-points. Maximum NV rate is defined using 'minimum fresh air requirements per person' and it is calculated as $m^3/s = \text{MinFreshAir} \times \text{NumberPeople}/1000$.

### 3.4. Biomimetic building envelope with PCM

In this scenario, the biomimetic building envelope has a 1 cm Bio-PCM layer integrated in the wall and roof assembly. Both MM and NV scenarios described above are simulated with an integrated Bio-PCM layer (i.e. MM-PCM and NV-PCM, respectively).

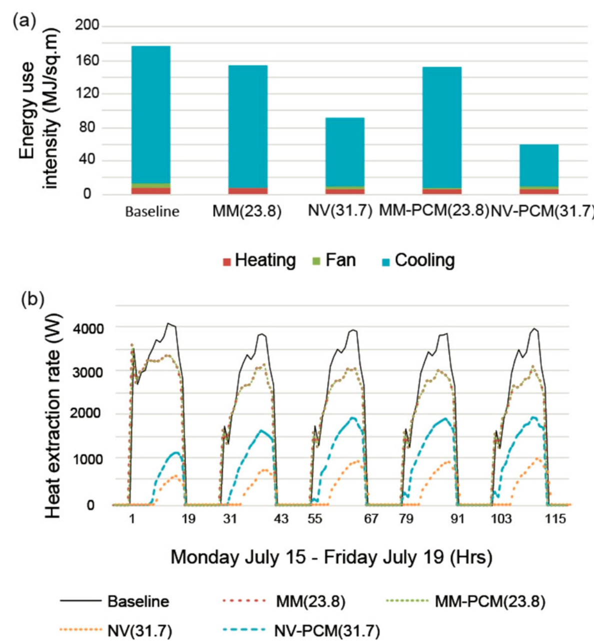


**Figure 6.** (a) Comparative HVAC specific EUI of different building envelopes where mixed mode (MM) scenario and MM in combination with phase change material (MM-PCM) scenario are tested at 23.8°C. Similarly, natural ventilation (NV) and NV in combination with PCM (NV-PCM) are tested at 31.7°C. (b) Comparative heat extraction rate of different building envelopes on the south zone of the middle floor during hottest weekdays of the year (Monday, July 15 to Friday, July19).

### 3.5. Comparative simulation results

Figure 6 shows the comparison of the HVAC-related energy use intensity (EUI) in the small-sized office building using the variations of the biomimetic building envelopes over the baseline envelope (Table 2). The HVAC-related EUI includes heating, cooling and fan energy. For our small office building, the summertime HVAC-related EUI is 59.4% of the total EUI of the building (297.88 MJ/m$^2$), which includes interior lighting, equipment and HVAC. The HVAC-related EUI presented in this paper is for summer months (April-September) only, where cooling energy need is very high (88.9%) compared to the heating and fan energy needs (see Figure 6(a)). The HVAC-related EUI is estimated by dividing the total HVAC-related energy (MJ) by the built-up area (m$^2$).

The baseline HVAC-related EUI is 177.0 MJ/m$^2$. The biomimetic envelope with an MM ventilation (MM(23.8)) saves 13% of HVAC-related EUI over the baseline scenario. This reduction over the baseline scenario is made possible by a reduction from 177.0 to 154.4 MJ/m$^2$ (Figure 6(a)). The majority of this saving is attributed to a reduction in cooling energy needs because it reduced conditioning needs when outside conditions were in a comfort range. The MM ventilation scenario with the Bio-PCM layer (MM-PCM (23.8)) reduced HVAC-related EUI by 14%. Because the role of PCM (absorbing sensible heat and delaying thermal lag) is quite limited when the thermal comfort range is limited to 21.1–23.8°C, there is almost no difference in energy savings. When we simulated the NV (31.7), HVAC-related EUI is reduced by 48% compared to the baseline scenario and 35% over the MM scenario (23.8). This reduction is made possible by 50% reduction in cooling energy need, although a slight increase in the fan energy is observed (Figure 6(a)). The NV scenario with the Bio-PCM layer (NV-PCM (31.7)) further increased cooling energy savings, leading to a reduction of HVAC-related EUI by 66%. The HVAC-related EUI is reduced to 59.4 MJ/m$^2$, which is the lowest among all scenarios. Thus for our best-case scenario, the total EUI of the building can be reduced by 39% (i.e. 59.4% of the HVAC-related EUI).

The energy reduction potential of each envelope is further analysed in Figure 6(b), which shows changes in the heat extraction associated with the cooling energy during the hottest week of the year, that is, July 15–21. Only the working days of the week are shown because cooling is turned off during weekdays. We chose to evaluate the south zone of the middle floor of the building because south wall presents maximum opportunity to save energy than other orientations through the year. Figure 6(b)) helps understand how the performance of the proposed envelopes varies on a daily basis. For example, cooling needs on Monday, July 15, are higher than Friday, July 19, where the energy saving potential of the NV scenario (31.7) is highest. The peak heat extraction rate in the baseline scenario (Figure 6(b), Baseline) is 4286 W and occurs at 3:00 pm. In comparison, the peak heat extraction in NV (31.7) at 3:00 pm is only 546 W. This is a reduction of 85%. The NV-PCM (31.7) scenario at 3:00 pm reduced heat extraction rate by 75%. The heat extraction rate of each envelope varies during the week changing its energy saving potential. For example, NV (31.7) reduced heat extraction rate by 87%, 81%, 76%, 77% and 76% during Monday through Friday, respectively. In comparison, NV-PCM (31.7) saves 75%, 59%, 53%, 52% and 53% during the week. The NV (31.7) scenario is showing maximum savings during the hottest week of the summer while the NV-PCM (31.7) scenario saves maximum energy across summer months. In this study, the envelope integrated Bio-PCM absorbs sensible heat and delays internal heat gain by the walls during occupied hours while natural ventilation provides comfort conditions in adaptable range. This strategy is best demonstrated when the ambient temperature is high and the use of mechanical system is minimal, like in NV-PCM (31.7). Therefore, highest savings are observed when the Bio-PCM and extended set-point at 31.7°C are combined.

## 4. Discussion

We adopted the solution-based approach presented by Badarnah and Kadri (2014) for developing a feasible biomimetic building envelope that reduces energy needs of a small-sized office building in hot-humid conditions. This approach provided a systematic biomimicry design process that helped us reach our goal: to emulate a practical and easily implementable design. However, we added one step to the described approach. Rather than directly abstracting biological strategies into design principles, we first investigated the thermal behaviour of the building in order to obtain a better understanding of the context of the biomimetic design. This allowed us to abstract the biological strategies into more suitable and applicable design principles.

Based on the building thermoregulation investigation, the African reed frog's ability to manipulate heat build-up and the Hercules beetle's ability to manage humidity were most inspiring for designs in hot-humid conditions. The African reed frog's physiological adaption strategies inspired us to use a high albedo surface, PCMs for delaying heat build-up, and explore adaptive thermal comfort strategies using MM and NV. The Hercules beetle's camouflage strategy of using ambient humidity for passive colour change inspired us to precondition outside air through dehumidification of incoming air (i.e. using hydrogels).

The strength of using a computational approach at the onset of the design process lies in the prospect of conducting a comparative analysis of different design components and thus better informed decision-making on the basis of the building's expected energy performance (Loonen et al. 2014). Moreover, the biomimetic design can be hypothesized to save energy, but computational calculations provide more insight under which environmental conditions and in which geographical locations energy savings are indeed achieved. The comparative energy simulations were important to show the energy saving contribution of each design component.

The energy comparisons showed the possibility of a 66% decrease in the HVAC-related EUI or 39% of the overall EUI, primarily for cooling during hot-humid summer months. This was achieved for the NV scenario with the Bio-PCM layer (NV-PCM (31.7)), whereas other scenarios had lower energy savings. This result shows that it was interesting to mimic both the African reed frog and the Hercules beetle, and that their strategies complimented each other to gain additional energy savings.

The biomimetic envelope system using MM and NV saved 13% and 48% energy, respectively, over the baseline code compliant air-conditioned small office building. The use of an adaptive thermal comfort model by extending set-points for an expanded thermal comfort range were particularly evident in improving energy savings by the biomimetic envelope systems using NV. The integration of a Bio-PCM layer was especially useful in saving additional energy during occupied hours when outside temperature was high and the use of mechanical system was minimal. While we choose a square building based on the most prevalent building form in the U.S., Olgyay (1963) recommended a rectangular building for hot-humid climates. It is thus possible that energy savings can be further improved when building forms and shape are adapted according to climate zone (Olgyay 1963). Indeed, the surface area of the south façade, which has the most heat gain, can be smaller in a square building than in a rectangular building, and thus more energy savings are possible.

Although living organisms and architectural buildings are very different in many ways, there are benefits from studying organisms' adaptation strategies, including physiological, morphological and behavioural strategies (Badarnah 2015). Especially when designing more responsive building envelopes, nature has shown to be one of the most prominent inspiration sources, as biological systems are inherently responsive to their environment (Loonen et al. 2013; Han, Taylor, and Pisello

2015; López et al. 2017). Biomimicry is a recently developed design methodology that assists in borrowing biological information to inspire new designs (Benyus 1997; Baumeister 2014). This fundamental work was adapted by Badarnah and Kadri who focused on biomimicry for creating architectural designs (2014). We based our study on their proposed solution-based approach. Our study had the objective to design a feasible biomimetic building envelope, which is why we designed it to be compatible with an existing curtain wall system. Although our decision perhaps limited the innovativeness of our design, the value lays in creating a biomimetic design that is feasible and practical to implement. We did not want to reinvent the entire building envelope, but rather explored the value of incremental improvements rather than radical innovation (Dewar and Dutton 1986).

Similarly, we looked for building materials that can be used for architectural purposes. Current manufacturing techniques do not yet yield building materials with the same functionality as nature, and especially not at affordable prices (Gruber and Jeronimidis 2012; Kennedy et al. 2015). For example, while the Hercules beetle uses an intricate multi-layer photonic structure, we chose to use more cost-effective hydrogels as they also reversibly and passively absorb moisture. Hydrogels have been recently suggested as a new architectural building material to improve thermoregulation (Ima Lab 2015), so our study encourages further development for such materials by providing additional evidence for their potential in creating energy-efficient building envelopes.

Each effort in applying biomimicry principles for designing innovative building envelopes identifies interesting biological strategies, provides insights in practical expectations and realizations, and contributes to building a more practical framework for facilitating the abstraction from biology into design principles. One important realization and exercise we had to go through was the abstraction level of the biological strategies, which can range from very literal to more metaphorical. To give an example, the most literal abstraction of the Hercules beetle's camouflage strategy would be: 'a hygroscopic nano-photonic material that leverages ambient humidity for adaptive colour changing'. Although this is the most accurate interpretation of the biological strategy, and thus likely to be an evolutionary beneficial strategy (Baumeister 2014), in this case, using this abstracted design principle would have limited the applicability and feasibility of a proposed biomimetic design. While it is important to maintain biological integrity, it is important to have enough creative freedom to develop a feasible biomimetic design for a desired context. In our study, we translated the 'hygroscopic nano-photonic material' simply into a hydrogel, because our desired outcome was not colour changing (which requires nanostructuring) but rather a (de)humidification function.

Our computational calculations show that our proposed biomimetic building envelope could result in up to 66% savings of HVAC-related EUI during summer months in Chicago. However, further empirical research is required to validate, test and enhance the application of our biomimetic building envelope. To further improve the sustainable outcome of the biomimetic building, ideally we would also include an ecosystem-level focus. Indeed, it is best to look at different emulation levels: form, process and ecosystem (Reap, Baumeister, and Bras 2005; Baumeister 2014; Kennedy et al. 2015). Once a geographical location is chosen, the building should be designed to fit within the urban microclimatic and the city context and explore which ecosystem services it can provide (Costanza et al. 1997; Bhiwapurkar 2016; Zari 2017). For example, we could investigate how recuperated water and heat from preconditioning the incoming air could be used not only within the building, but also among buildings within the city. A systems approach would recognize that using high albedo surfaces and phase change materials could also influence the thermal behaviour of the surrounding buildings (Santamouris, Synnefa, and Karlessi 2011).

## 5. Conclusion

The adoption of the solution-based approach described by Badarnah and Kadri (2014) assisted us in the development of a biomimetic building envelope that lowers energy consumption while minimizing energy needs for thermoregulation in a hot-humid climate. We used an energy simulation tool to first investigate the thermal behaviour of a building, providing us a better understanding of the design context, and to evaluate the potential energy savings of the biomimetic design. A comparative analysis indicated that the highest energy savings were obtained when the biomimetic design components of both the African reed frog and the Hercules beetle were combined. Our maximum calculated energy saving resulted in a 66% decrease in the HVAC-related EUI (or 39% of the total energy use of the building). Importantly, this could further be enhanced when also taking into account the form and shape of the building (Olgyay 1963).

## Acknowledgements

The authors would like to acknowledge the valuable architectural design input by S. Bennet and J.A. Ury, who also created Figures 2 and 5. The authors thank M. Shawkey, D. Baumeister and P. Niewiarowski for reviewing this manuscript and offering insightful feedback prior to submission.

## Disclosure statement

No potential conflict of interest was reported by the author.

## ORCID

*Daphne Fecheyr-Lippens* http://orcid.org/0000-0001-8096-5272
*Pravin Bhiwapurkar* http://orcid.org/0000-0002-7456-4605

## References

Armstrong, Rachel. 2012. *Living Architecture: How Synthetic Biology Can Remake Our Cities and Reshape Our Lives*. TED books.

ASHRAE. 2004. *Standard 55 – Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

ASHRAE. 2013. *Standard 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Badarnah, Lidia. 2015. "A Biophysical Framework of Heat Regulation Strategies for the Design of Biomimetic Building Envelopes." *Procedia Engineering* 118: 1225–1235.

Badarnah Kadri, L. 2012. "Towards the LIVING Envelope: Biomimetics for Building Envelope Adaptation." Doctoral Thesis, TU Delft, Delft University of Technology.

Badarnah, Lidia, and Usama Kadri. 2014. "A Methodology for the Generation of Biomimetic Design Concepts." *Architectural Science Review* (June): 1–14. doi:10.1080/00038628.2014.922458.

Baumeister, Dayna. 2014. *Biomimicry Resource Handbook: A Seed Bank of Best Practices*. Biomimicry 3.8.

Benyus, Janine M. 1997. *Biomimicry: Innovation Inspired by Nature*. New York, NY: William Morrow.

Bhiwapurkar, P. 2015. "Urban Climate Change Impacts on Building Heating and Cooling Energy Demand." In *Architectural Research Centers Consortium Conference*, 270–278.

Bhiwapurkar, P. 2016. "Bioclimatic Design and Urban Microclimate." In *PLEA 2016: 32nd International Conference on Passive and Low Energy Architecture*, Vol. 1, 1373–1380.

Bhiwapurkar, Pravin, and Demetrios Moschandreas. 2010. "Street Geometry and Energy Conservation of Urban Buildings in Chicago." *Intelligent Buildings International* 2 (4): 233–250.

Brager, Gail, and Lindsay Baker. 2009. "Occupant Satisfaction in Mixed-Mode Buildings." *Building Research & Information* 37 (4): 369–380.

Brager, Gail, Hui Zhang, and Edward Arens. 2015. "Evolving Opportunities for Providing Thermal Comfort." *Building Research & Information* 43 (3): 274–287.

CBECS. 2012. "2012 Commercial Buildings Energy Consumption Survey (CBECS) Preliminary Results." http://www.eia.gov/consumption/commercial/reports/2012/preliminary/index.cfm.

Chayaamor-Heil, Natasha, and Nazila Hannachi-Belkadi. 2017. "Towards a Platform of Investigative Tools for Biomimicry as a New Approach for Energy-Efficient Building Design." *Buildings* 7 (1): 19. doi:10.3390/buildings7010019.

Costanza, R., R. d'Arge, R. de Groot, S. Faber, M. Grasso, B. Hannon, K. Limburg, et al. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature* 387 (6630): 253–260.

de Dear, R., and Gail Schiller Brager. 2001. "The Adaptive Model of Thermal Comfort and Energy Conservation in the Built Environment." *International Journal of Biometeorology* 45 (2): 100–108.

de Dear, Richard J., and Gail S. Brager. 2002. "Thermal Comfort in Naturally Ventilated Buildings: Revisions to ASHRAE Standard 55." *Energy and Buildings*. Special Issue on Thermal Comfort Standards 34 (6): 549–561.

DesignBuilder Software Ltd. n.d. "DesignBuilder: EnergyPlus Simulation." https://www.designbuilder.co.uk/simulation.

Dewar, Robert D., and Jane E. Dutton. 1986. "The Adoption of Radical and Incremental Innovations: An Empirical Analysis." *Management Science* 32 (11): 1422–1433.

Fernández, Cadenas, Mario, and Francisco Javier Neila Gonzalez. 2015. "Biomimicry in Climate Adaptive Building Skins: Relevance of Applying Principles and Strategies." In *VII International Congress on Architectural Envelopes*. ICAE 2015, 27–29 May, Donostia - San Sebastián.

Gebeshuber, I. C., and M. Drack. 2008. "An Attempt to Reveal Synergies Between Biology and Mechanical Engineering." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 222 (7): 1281–1287.

Geise, W., and K. E. Linsenmair. 1986. "Adaptations of the Reed Frog *Hyperolius viridiflavus* (Amphibia, Anura, Hyperoliidae) to Its Arid Environment. IV. Ecological Significance of Water Economy with Comments on Thermoregulation and Energy Allocation." *Oecologia* 68 (4): 542–548.

Gostonyi, S. 2013. BioSkin–Research Potentials for Biologically Inspired Energy Efficient Façade Components and Systems. *Final Report FFG, Vienna*.

Gruber, Petra, and George Jeronimidis. 2012. "Has Biomimetics Arrived in Architecture?" *Bioinspiration & Biomimetics* 7 (1): 10201. doi:10.1088/1748-3182/7/1/010201.

Han, Yilong, John E. Taylor, and Anna Laura Pisello. 2015. "Toward Mitigating Urban Heat Island Effects: Investigating the Thermal-Energy Impact of Bio-Inspired Retro-Reflective Building Envelopes in Dense Urban Settings." *Energy and Buildings* 102 (Sept.): 380–389.

Huang, Jianhua, and Kevin Robert Gurney. 2016. "The Variation of Climate Change Impact on Building Energy Consumption to Building Type and Spatiotemporal Scale." *Energy* 111 (Sept.): 137–153.

Ima Lab. 2015. "Hydrogel-Filled Ceramics for Cool Buildings." http://www.imalab.net/news/hydrogel-filled-ceramics-cool-buildings.

Kennedy, Emily, Daphne Fecheyr-Lippens, Bor-Kai Hsiung, Peter H. Niewiarowski, and Matthew Kolodziej. 2015. "Biomimicry: A Path to Sustainable Innovation." *Design Issues* 31 (3): 66–73.

Kobelt, Frank, and K. E. Linsenmair. 1986. "Adaptations of the Reed Frog *Hyperolius viridiflavus* (Amphibia, Anura, Hyperoliidae) to its Arid Environment. I. The Skin of *Hyperolius viridiflavus nitidulus* in Wet and Dry Season Conditions." *Oecologia* 68 (4): 533–541.

Kobelt, F., and K. E. Linsenmair. 1992. "Adaptations of the Reed Frog *Hyperolius viridiflavus* (Amphibia, Anura, Hyperoliidae) to Its Arid Environment. VI. The Iridophores in the Skin as Radiation Reflectors." *Journal of Comparative Physiology. B, Biochemical, Systemic, and Environmental Physiology* 162 (4): 314–326.

Kośny, J., N. Shukla, and A. Fallahi. 2013. *Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern U.S. Climates*. Golden, CO: U.S. Dept. of Energy, Energy Efficiency & Renewable Energy, Building Technologies Program.

Lampert, Kathrin P. 2001. "Alternative Life History Strategies in the West African Reed Frog, *Hyperolius nitidulus*." Unpublished diss., Universität Würzburg.

Lampert, Kathrin P., and Eduard K. Linsenmair. 2002. "Alternative Life Cycle Strategies in the West African Reed Frog *Hyperolius nitidulus*: The Answer to an Unpredictable Environment?" *Oecologia* 130 (3): 364–372. doi:10.1007/s00442-001-0821-4.

Levy-Lior, Avital, Boaz Pokroy, Berta Levavi-Sivan, Leslie Leiserowitz, Steve Weiner, and Lia Addadi. 2008. "Biogenic Guanine Crystals from the Skin of Fish May Be Designed to Enhance Light Reflectance." *Crystal Growth & Design* 8 (2): 507–511.

Levy-Lior, Avital, Eyal Shimoni, Osip Schwartz, Efrat Gavish-Regev, Dan Oron, Geoff Oxford, Steve Weiner, and Lia Addadi. 2010. "Guanine-Based Biogenic Photonic-Crystal Arrays in Fish and Spiders." *Advanced Functional Materials* 20 (2): 320–329.

Loonen, R. C. G. M., S. Singaravel, M. Trčka, D. Cóstola, and J. L. M. Hensen. 2014. "Simulation-Based Support for Product Development of Innovative Building Envelope Components." *Automation in Construction* 45 (Sept.): 86–95.

Loonen, R. C. G. M., M. Trčka, D. Cóstola, and J. L. M. Hensen. 2013. "Climate Adaptive Building Shells: State-of-the-Art and Future Challenges." *Renewable and Sustainable Energy Reviews* 25 (Sept.): 483–493.

López, Marlén, Ramón Rubio, Santiago Martín, and Santiago Ben Croxford. 2017. "How Plants Inspire Façades. From Plants to Architecture: Biomimetic Principles for the Development of Adaptive Architectural Envelopes." *Renewable and Sustainable Energy Reviews* 67 (Jan.): 692–703.

López, Marlén, Ramón Rubio, Santiago Martín, Ben Croxford, and Richard Jackson. 2015. "Active Materials for Adaptive Architectural Envelopes Based on Plant Adaptation Principles." *Journal of Facade Design and Engineering* 3 (1): 27–38.

Mazzoleni, Ilaria. 2013. *Architecture Follows Nature: Biomimetic Principles for Innovative Design*. Boca Raton, FL: Taylor and Francis.

Olgyay, Victor. 1963. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton, NJ: Princeton University Press.

Phase Change Energy Solutions. 2005. "BioPCM Uses Physics to Enhance Occupant Comfort, Reduce HVAC Loads and Save Energy." http://www.phasechange.com.

Rassart, M., J.-F. Colomer, T. Tabarrant, and J. P. Vigneron. 2008. "Diffractive Hygrochromic Effect in the Cuticle of the Hercules Beetle Dynastes Hercules." *New Journal of Physics* 10 (3): 33014. doi:10.1088/1367-2630/10/3/033014.

Reap, John, Dayna Baumeister, and Bert Bras. 2005. "Holism, Biomimicry and Sustainable Engineering." Proceedings of IMECE 2005, Orlando, FL.

Richman, Eric E., Emily M. Rauch, Jaclyn N. Phillips, Kimberly A. Petty, Jessica Knappek, and Priscilla L. Lopez-Rangel. 2008. *National Commercial Construction Characteristics and Compliance with Building Energy Codes: 1999–2007*. PNNL-SA-59829. Richland, WA: Pacific Northwest National Laboratory (PNNL).

Santamouris, M., A. Synnefa, and T. Karlessi. 2011. "Using Advanced Cool Materials in the Urban Built Environment to Mitigate Heat Islands and Improve Thermal Comfort Conditions." *Solar Energy*. Progress in Solar Energy 2. 85 (12): 3085–3102.

Schittich, C., W. Lang, and R. Krippner. 2006. *Building Skins*. München: Walter de Gruyter.

Schmuck, R., F. Kobelt, and K. E. Linsenmair. 1988. “Adaptations of the Reed Frog *Hyperolius viridiflavus* (Amphibia, Anura, Hyperoliidae) to Its Arid Environment. V. Iridophores and Nitrogen Metabolism.” *Journal of Comparative Physiology. B, Biochemical, Systemic, and Environmental Physiology* 158 (5): 537–546.

Sharma, Atul, V. V. Tyagi, C. R. Chen, and D. Buddhi. 2009. “Review on Thermal Energy Storage with Phase Change Materials and Applications.” *Renewable and Sustainable Energy Reviews* 13 (2): 318–345.

Speck, T., and O. Speck. 2008. “Process Sequences in Biomimetic Research.” *Design and Nature IV* 114: 3–11. doi:10.2495/DN080011.

Sun, Jiyu, Bharat Bhushan, and Jin Tong. 2013. “Structural Coloration in Nature.” *RSC Advances* 3 (35): 14862–14889.

Thornton, Brian A., Weimin Wang, Yunzhi Huang, Michael D. Lane, and Bing Liu. 2010. *Technical Support Document: 50% Energy Savings for Small Office Buildings*. Richland, WA: Pacific Northwest National Laboratory.

U.S. Energy Information Administration (eia). 2013. “Heating and Cooling No Longer Majority of U.S. Home Energy Use.” *Today in Energy*, March. https://www.eia.gov/todayinenergy/detail.php?id = 10271.

Vattam, Swaroop S., Michael E. Helms, and Ashok K. Goel. 2009. “Nature of Creative Analogies in Biologically Inspired Innovative Design.” Proceedings of the Seventh ACM Conference on Creativity and Cognition, 255–264. C&C ‘09, New York, NY, USA: ACM. doi:10.1145/1640233.1640273.

Weissburg, Marc. 2016. “The Ecology of Human Infrastructure.” *Zq 17*, October 5.

Whitesides, George M., and Bartosz Grzybowski. 2002. “Self-Assembly at All Scales.” *Science* 295 (5564): 2418–2421.

Zari, Maibritt Pedersen. 2010. “Biomimetic Design for Climate Change Adaptation and Mitigation.” *Architectural Science Review* 53 (2): 172–183.

Zari, Maibritt Pedersen. 2017. “Biomimetic Urban Design: Ecosystem Service Provision of Water and Energy.” *Buildings* 7 (1): 21. doi:10.3390/buildings7010021.

Zohuriaan-Mehr, Mohammad J., and Kourosh Kabiri. 2008. “Superabsorbent Polymer Materials: A Review.” *Iranian Polymer Journal* 17 (6): 451.