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SolarLeaf is the world's first bioreactive façade, generating biomass and heat in a closed loop system. This article discusses the technology, the first monitoring results and future potentials.

# SolarLeaf: The world's first bioreactive façade

*Jan Wurm and Martin Pauli*

Photobioreactors are transparent containers for the controlled cultivation of micro-organism such as algae. The BIQ house is the world's first architectural project that features flat panel photobioreactors, generating biomass and heat as part of an integrated energy strategy. The project is part of the International Building Exhibition (IBA) in Hamburg. Since the official opening of the project in April 2013, the performance of the system has been continuously monitored. This article describes the design concept and the façade system in detail. The assumptions at design stage are compared with the findings from project monitoring and opportunities for further development are identified.

The initial design concept was developed for an international design competition calling for a 'Smart Material House' as part of the 2013 Hamburg IBA. The design team included SPLITTERWORK architects from Austria, Arup Germany for building envelope design, Bollinger & Grohmann as structural engineers, and Immosolar for energy consulting.[1] The original idea was for a 'house in a house concept' where the stacked residential units were enclosed by a secondary skin composed of bioreactors, some active, some transparent, without functionality. We based the concept on the first flat panel bioreactor design by Hamburg-based research company Strategic Science Consult (SSC) consisting of two bonded sheets of deep drawn polycarbonate.

After the project was awarded a first prize in spring 2010, Arup initiated a consortium to develop a photobioreactor (hereafter pbr) façade system for building integration, also sometimes called the bioreactive façade, including SSC as experts for micro-algae technology and processing and Colt International as a specialist contractor for secondary façade systems. The consortium received funding from German funding body 'ZukunftBau'. Flat panel bioreactors made of glass were developed and tested. The associated façade system was branded 'SolarLeaf' by the developing consortium.

In parallel, Otto Wulff Bauunternehmung from Hamburg, a private investor, signed up to develop the residential project further under the name 'BIQ_house'. As part of the redesign, the double skin concept was dropped and instead clusters of pbr were fixed, as a secondary system, directly on to the primary façade. The development of the project for the façade system and the IBA project subsequently merged and supported each other. SSC took over the role of co-investor to develop the pilot installation of the bioreactive façade. Arup developed the energy concept and designed the mechanical systems, while Colt supplied and fitted the pilot installation of the SolarLeaf façade.

After the official opening of the BIQ house on 30 March 2013, Arup was commissioned to lead the monitoring of the project together with Colt, SSC and Professor Ingrid Breckner from HafenCity University Hamburg, also funded by ZukunftBau. Monitoring of the project was completed in spring 2015.

## Systems and technology

The idea for the system design is based on the earlier work of former Arup director Peter Head. In his lecture and pamphlet *Entering the Ecological Age* from 2008, he described the potential benefit of tubular pbr integrated within building skins. The pbrs allow short carbon cycles, as fast growing micro-organisms consume CO2 and prevent emissions being released to the atmosphere. Another source of inspiration is the production facility based on tubular reactors with a photoactive volume of 600m$^2$ operated by Bioprodukte Professor Steinberg, where micro-algae for the pharmaceutical industry have been produced on a commercial level since 2000.

The competition concept featured flat panel pbr oriented to all four sides of the buildings. Functionalities included the generation of heat through the solar thermal effect, the production of micro-algae for conversion to methane on site and a link to the heating system of a nearby public swimming pool to absorb CO2 emissions throughout the year. The strength of the original concept was to showcase the benefits of the system on a district scale rather than simply on the scale of an individual building. In the design stage following the competition, however, the system was developed as a 'stand-alone' system to mitigate the risk of implementing such an experimental technology.

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The BIQ project, as built, features four storeys and a penthouse with a gross floor area of 1,600 m² and fifteen residential units between 50 and 120 m² *[1]*. The house is certified as a Passive House with a heating demand of less than 15 kWh per square metre per year. This is achieved by high thermal insulation for opaque areas and glazing units, an efficient heating system and a mechanical ventilation system with heat recovery.

One hundred and twenty-nine storey-high bioreactors have been installed on the southwest and southeast facing façades with an active surface area of approximately 185 m². All the pbr panels of one floor are grouped forming a closed loop system. Pumps circulate the algae fluid from the plant room to the façade panels. At the plant room the algae are 'fed' by the intake of nutrition and compressing flue gas from a gas boiler on site and releasing it into the medium. The proportion of the carbon that can be dissolved by the medium limits the number of panels per group. The photosynthetic process of the algae is initiated when exposed to the daylight in the façade panels. The process is accelerated by the periodic release of pressurised air at the bottom edge of each pbr. The turbulence generated through this uplift technology stimulates the metabolism of the micro-algae and subsequently increases the productivity of the system. The processing of the algae from feeding to harvesting is controlled by a fully automated system.

Micro-algae absorb daylight in a relatively narrow part of the solar spectrum with its peak at approximately 640 nm. The remaining part of the daylight spectrum entering the pbr is absorbed and transformed into heat, which leads to a rise in the temperature of the medium. The species generally cultivated at the BIQ is a local strain of the Chlorella Vulgaris, well adapted to the climate conditions with a photochemical activity between 8 °c and 38 °c. In order to maintain the cultivation of micro-algae, the excess of heat has to be released from the system by means of heat exchangers.

The solar thermal effect of the pbr – a negative side-effect for open field applications – has a positive impact when integrated on a building as the recovered heat can be used to contribute to the inhabitants' demand for heat and hot water.

The building service system at the BIQ House is designed to allow for the flexible use of the solar thermal heat generated. At the beginning and end of the heating season (during spring and autumn) the temperature of the harvested heat could be directly raised to the required level of the heating system by means of a heat pump. During summer times where there is no heat demand and very limited demand for hot water, geothermal probes beneath the foundations can store heat. Alternatively heat can be fed into the district heating system of the municipality of Hamburg, to which the BIQ house is connected. The district heating also represents a robust fallback in case the heat demand exceeds the production of the façade.

The biomass is harvested in a continuous process or in batches using a floatation device. The harvested biomass is processed offsite mainly for research purposes aiming to create a value chain for the food and the pharmaceutical industry. For the coming



1 BIQ house in Hamburg, Germany, with 128 bioreactive façade panels.





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year, an onsite extraction of ingredients such as amino acids and lipids is scheduled. If successful this would be a breakthrough as the extracts could be easily stored, transported and sold strengthening the business case for the installation of bioreactive façades.

At the design stage the energy conversion rate was simulated to approximately 40% for heat and 8% for biomass.

### Façade design

The vertical elements have a size of 2.5 x 0.7 m. Each panel can rotate along its vertical axis for maintenance. The frame is formed from extruded aluminium profiles. Each panel is approximately 80mm deep. The build-up of the glass bioreactor features a total of three cavities. The central cavity is 18mm wide traversed by approximately 24 litres of aqueous medium. The flanking glass sheets are made of extra clear fully toughened soda lime glass captured at all edges providing a continuous seal. The outer cavities represent a standard cavity known from double-glazed units to insulate the medium and minimise heat losses. The outer sheet of glass is a laminated safety glass to contain the fragments if one of the inner glass panes breaks. Most of the outer glass surfaces features a micro-texture to minimise reflections and maximise the productivity of the bioreactor.

Each pbr is serviced through the bottom edge of the panel. Pressurised air is pushed through three valves as large bubbles into the central cavity generating turbulences. The inner surfaces of the panels are washed by these turbulences, by a mixture of water and air that keeps the panes free of organic deposits. Each panel is linked to the parallel circuit of the closed loop by an intake and outtake for the medium. All piping is installed horizontally along an insulated duct that can be maintained from the outside through revision flaps. With respect to the design, the hydrostatic pressure of 2.5 m leads to the relatively narrow width of the panel to limit glass thickness and weight. An ongoing research project is investigating bigger panels allowing a higher degree of architectural flexibility by including bonded stiffeners into the cavity. The system underwent extensive testing to gain building approval in Germany.

### Monitoring

In order to understand this potentially disruptive technological innovation, technical, ecological, and social aspects need to be looked at holistically to optimise and develop the system towards market maturity. In the foreground of this monitoring project was the intensive evaluation and optimisation of energy efficiency and the technology, and a study of the system's reception among building users. Based on specific local conditions, several scenarios for optimisation have been developed over the monitoring period of two years. Alongside the analysis of user acceptance, public responses in the national and international media have also been recorded.

After completion of the monitoring in spring 2015, it can be stated that the technical feasibility has been fully proven. The system performed well despite ongoing minor technical challenges that are to be expected in a pilot installation. Heat and biomass have been constantly produced. However the total combined output of heat and biomass of approximately 26,000 kWh per annum is approximately half of what has been expected. The heat gain has been approximately 22,500 kWh, resulting in an energy conversion of sunlight into heat of 21%, in contrast to the 40% simulated at the design stage. The gain of algae biomass is 600 kg per year, equivalent to 4,539 kWh, which corresponds to an energy conversion factor 4.4% in relation to solar radiation gain. At the design stage 8% was predicted. A positive surprise was the consistent acceptance of the users, who demonstrated an emotional link with the bioresponsive algae system.

The development, implementation, and optimisation of the bioreactive façade and the building service systems constitute a big success. The system is currently being upgraded technically in order to achieve more efficient and resilient performance, meeting the performance that had been set previously. The monitoring methodology and results are discussed in the following sections.

### Monitoring methodology

Based on defined components and implemented sensor technology, the monitoring has been conducted on the basis of frequent maintenance and inspections, as well as an ongoing evaluation of different measurements. Critical parameters with respect to visual, acoustic, and olfactory comfort have been defined. Maintenance and inspection results have been recorded and technical problems have been constantly analysed in order to adjust and optimise the operation of the system.

Weather data (global radiation) and associated gains of light, heat, and biomass have been measured in order to quantify the energy conversion and compare the system with other systems on the market. This understanding of the correlations between external conditions and system performance allows energy efficiency for other climatic and geographic contexts to be predicted. The productivity of the system with respect to the generation of biomass is influenced by key process parameters, such as the supply rate of nutrients, the pH-value as well as cell density, and the temperature of the medium. All these factors have been intensively monitored.

Besides the production of heat and biomass, the bioreactive façade enables the absorption of carbon dioxide that results from the flue gas of the building. This ecosystem service is an added value that contributes to the overall performance of the system. The process of carbon absorption has been measured and balanced. In order to assess the overall efficiency and economic feasibility of the system, the electrical energy input constitutes a critical factor, especially in relation to the gain of energy and biomass.



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Therefore, all electrical energy usage has been measured and captured automatically.

The social acceptance analysis comprised seven phases:

1. expert interviews regarding the construction of the system;
2. expert interviews regarding functionality and operation of the technology;
3. description of the building as a techno-social system with varying challenges for involved stakeholders with differing expertise;
4. expert interviews with technical advisors;
5. interviews with users with respect to their experience and impact on their quality of life;
6. evaluation of user interviews and comparison with the results of expert interviews;
7. comparison with the assessment of the results from other monitored projects at the IBA.

### Monitoring technical performance, energy consumption, and generation

Both the bioreactor and the building services system are highly innovative. The BIQ house serves as a pilot project for both technologies. Based on constant technical and process optimisation, a performing system has been established and operated for the past two years. The technical problems and their correlation with the energy performance and user acceptance are shown in a table below (Table *[1]*). Due to the fact that the bioreactor technology is disconnected technically from the apartments, recurring problems have only been noticed by the users if they had visual or acoustical implications. The operation of the system had no direct effect on user acceptance. Beside minor technical challenges that have been analysed and solved as the system was monitored, the two main problems have been: insufficient heat exchangers; and the corrosion of aluminium distance frames within each reactor due to very high local pH-values, up to pH-12.

The heat exchangers were replaced in spring 2014 and the implications on the energy performance were significant. A substitution strategy for the aluminium frames has been developed in collaboration with external industry partners such as SIKA in order to achieve a resilient solution capable of withstanding the chemical environment resulting from the alkaline aqueous medium. In September 2015, the BIQ house was fitted with a new generation of reactors.

During the entire monitoring period, the system could not be operated in the way it was designed because of technical problems resulting from the lack of sufficient heat exchangers (mainly in 2013) and the clogging of the intake and outtake of the medium due to the by-products of the corroding aluminium frames. Both problems led to significantly reduced gain of heat and biomass.

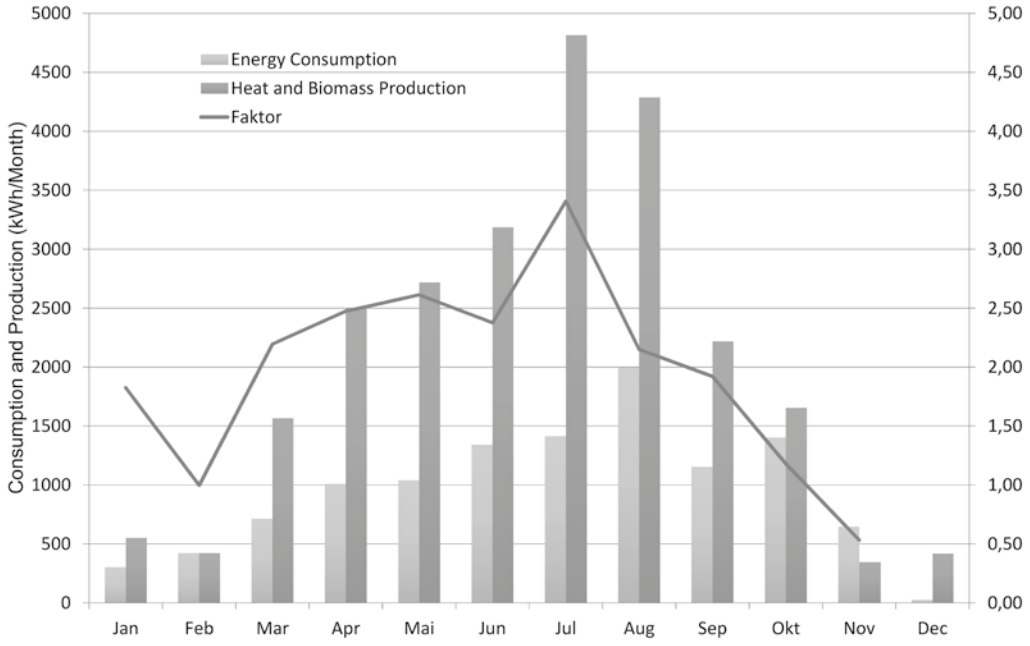
Although data was recorded throughout the two-year period meaningful measurements where only achieved during short timeframes. The following assessment is based on data generated from 1 January 2014 until 31 December 2014 *[2]*. Global radiation data has been obtained from the official measuring point at Hamburg Fuhlsbüttel. For tracking heat production, manually and automatically recorded data sources were employed. Due to the fact that pipework has been partly blocked, the filling level of the reactor has been limited to 1.9 m (instead of 2.3 m). Therefore, the measured heat gains have been achieved with an active area of 135 $m^2$ (129 reactors x 0.55 m x 1.90 m). This area represents only 73% of a possible active area of 185 $m^2$, given the normal filling level of 2.6 m. As the energy consumption is dependent on the size of the system, it can be stated that the energy efficiency could be significantly improved by larger scale system.

During the entire year, the southeast-facing façade was exposed to 25% more solar radiation than the southwest façade. The annual sun exposure for 135 sqm active façade area was 75,095 kWh. This value has been extrapolated for an area of 185 sqm. Therefore a sun exposure of 102,909 kWh/a was used for further calculations.

| Component | Technology | Energy | Sociology |
|---|---|---|---|
| Photobioreactor glass panes | Glass breakage resulting from maintenance, damaged glass panes have been replaced | Marginal implication, every faulty reactor cannot produce heat and biomass | Damage has been noticed by users, negative reactions on blogs |
| Aluminium distance frames | Corrosion of aluminium distance frames within the reactors due to high pH-values (pH-14), replacement of distance frames with FRP | Corrosion particles congested piping system and had significant impact on the production of energy and biomass | No direct implications |
| Heat exchanger | Insufficient cooling in summer | Insufficient temperature consistency, causing lower biomass production | No direct implications |
| Pipe connections | Frost damage, exchange of damaged components | No direct implications | Problem has been noticed by one building occupant |
| Control valve | Faulty circuit/leakage | Lower production of heat and biomass due to wrong operation | No direct implications |
| Saturation facility | Insufficient saturation | Supply with $CO_2$ is critical, therefore lower biomass production | No direct implication |
| Airlift | High frequency has been reduced | Reduction of too high frequency caused significant savings of primary energy without loss of overall performance | Less acoustic emissions increased acceptance |

Table 1. **Overview of technical challenges.**


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2 Annual energy consumption and production of biomass.

With respect to the heat gain there have been significant variations due to the installation of new heat exchangers. For an area of 185 sqm an annual heat gain of 21,626 kWh has been calculated. This value leads to a conversion efficiency factor of 21%. The factor simulated at design stage was approximately 40%. In principle, higher efficiencies can be achieved if heat losses in the piping system are eliminated and an operation with standard filling level can be achieved.

Regarding the conversion of sunlight into biomass, the productivity correlates with temperature levels of the medium. The malfunctioning heat exchangers led to temperature levels within the reactors that were too high and poor conditions for algae growth. Despite this, approximately 600kg per annum have still been harvested. This represents 4,539 kWh for the year 2014. Therefore the conversion efficiency is 4.4%, which is 50% below the expected value.

The energy consumption to operate the system was 11,471 kWh in 2014. It is expected that this value can be reduced significantly due to further system optimisation. This energy demand has been partly covered by PV-facilities on the roof of the BIQ house.

At this stage, only a relatively small amount of the total solar radiation can be transformed into usable energy in form of heat and biomass. In the first two years the system exhibits a utilisation factor of 25.4% which is relatively low compared with state-of-the-art solar thermal collectors (50% to 60%). Solar thermal systems do not, of course, feature additional functionalities like biomass production and absorption of CO2. However, most importantly the system has a net energy gain. Taking the solar radiation at the bioreactors into account, the utilisation ratio amounts to 37.9%. In contrast to the original conception the gained heat has not been used for the building itself (heating and freshwater). The operator sold the majority of heat to the local district heating provider.

**Monitoring social acceptance**

Due to the technological novelty, there was no previous experience the possible influence of the façade upon the residents' day-to-day lives. Therefore, four research questions were posed:

- What types of people are attracted by the BIQ and are interested in renting a flat?
- How do the residents perceive the algae façade in their daily life with regard to acoustic noise, colour, bubbling, vibration, and cleanliness?
- What potential does the algae façade have to create identity with respect to the residents' quality of life?
- What implementation strategy could be developed based on knowledge gained from the project?

None of the tenants/households interviewed has rented their flat because of the façade technology. They instead report that their decisions were informed because of the quality of the flat itself and the favourable location of the BIQ building in Hamburg, with good access to public transport. They were all open to the technology although not without a little scepticism. This occurred, because the system cannot be decoded by laypeople beforehand. The residents' need for information and explanation was therefore strong. The residents' acceptance was achieved without significant problems, after an acoustic issue within the building had been solved. There were no aesthetic reservations. Three phases of gaining acceptance have been identified: In the first phase from April to June 2013 the residents approached the technology without any reservation. In a second phase from



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summer 2013 until around February 2014, maintenance work tested the patience of those residents (who were hoping for a shorter launch phase of the system). A third phase has followed since then, in which the residents have been hardly aware of the technology in their daily life, which was what the developer had hoped for.

From the perspective of innovation processes and the market introduction of the technology, a thorough understanding of the performance of the system has been achieved, which is a significant progress and an indicator for a relatively high level of product maturity. The façade will be further adapted to address new requirements. The experts involved will strive to maintain a sensitive approach to the residents to keep-up their identification with the project. Ongoing communications with residents who live next to the façade may also serve to prevent them from becoming dis-satisfied with the technology.

A comparison conducted by HafenCity University discovered that the user acceptance of the BIQ project is above other projects in the surrounding IBA development. In those other contexts, new technologies have been tested as well, although in those cases residents have endured significant disadvantages in their quality of life because of the functional and monetary risks in the acquisition of these experimental properties, which have led to major conflicts in the owners' community. There have been differing views between residents about the financial expense of green technologies because of the immaturity of some of the products tested. Such problems have not been identified at the BIQ house. In this case, the residents have not questioned the vertical farm approach to energy generation and biomass. Instead it has become clear that, where issues have occurred, they can be tracked back to well-understood material or mechanical factors in the system's operation that can be solved in future designs.[3]

## Conclusion

To summarise the conclusions of this study, despite the technical complexity of BIQ, few technical problems have occurred. Issues preventing standard operation after two years were the insufficient heat exchanger replaced in 2014 and the corrosion of anodised aluminium components located inside the bioreactor. The insufficient heat exchanger led to a lower filling volume, causing a reduced production of heat and biomass in 2013. The corrosion of the distance frame caused an irreversible congestion of the nutrient supply facilities, resulting in a significantly lower production of heat and biomass in 2014. The aluminium components have been substituted in September 2015. Currently, estimated energy conversion factors are 50% lower than anticipated. However higher values are likely to be achieved once the new reactor has been launched. That generation will feature more resilient components and an increased diameter of piping connections, leading to a more effective supply of $CO_2$ and nutrients and improved heat management in order to provide the right algae environment. Moreover, optimising the operation may further reduce energy consumption. Despite the technical challenges, however, the system produces a net energy gain. With respect to user acceptance, the results have been very reassuring. Acceptance has been constantly high after minor adjustments were made at the beginning of the monitoring period. According to regular interviews, building tenants did not perceive visual or olfactory burdens although acoustical emissions have caused occasional complaints.

## Prospect

After this successful implementation of the system, proving its feasibility, a big step has been taken towards market maturity. Further improvements with respect to efficiency will justify the comparatively large up-front investment and engage investors to implement the system more widely. Crucial will also be the implementation of a value chain of algal biomass for the pharmaceutical and the food industry. The onsite extraction of constituents, to be tested in 2016 at the BIQ house, will be major step towards a commercial feasibility of the system in this respect.

In the near future, the system will be scaled-up and implemented on district level in order to benefit from resource streams such as grey water and organic waste. Within a closed loop district system, the technology can serve as an absorber of emitted carbon as well as a decentralised water treatment facility using the finite resources within the grey water streams to feed the algae.

An ongoing collaborative research project investigates increasing the size of the bioreactor panel using structural sealant technology. The aim is the integration of these larger scale elements in unitised façade systems to support the installation at larger scale commercial developments.

This demonstration of the technical feasibility of integrating biochemical processes in the mechanical system of a building has led to a series of associated research projects around the world, partly funded by government bodies and partly funded by private corporations. Findings will push the state-of-the-art further in the next decade and a rapid increase of innovations in this field of research can be expected.


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## Notes

1. Available online: <http://www.iba-hamburg.de/en/projects/the-building-exhibition-within-the-building-exhibition/smart-material-houses/biq/projekt/biq.html> [accessed 15 March 2016].
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## Illustration credits

**arq** gratefully acknowledges:
Arup, SSC, Colt, 1
Arup, 2

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## Authors' biographies

After receiving his PhD from RWTH Aachen, Jan Wurm joined Arup London in 2005. Since 2008, he has been based in Berlin leading the Materials Practice and holding the firm's research portfolio in Europe. An architect with a deep technical understanding, Jan has steered a number of successful product developments, such as the SolarLeaf Façade.

Martin Pauli received a Master's degree in architecture before working at Arup. His professional focus is innovation and product management, working at the interface of Arup's Materials Consulting and Foresight Practice. Martin is regularly invited to national and international conferences. He lectures widely on the transition in our built environment from energy efficiency towards resource effectiveness.

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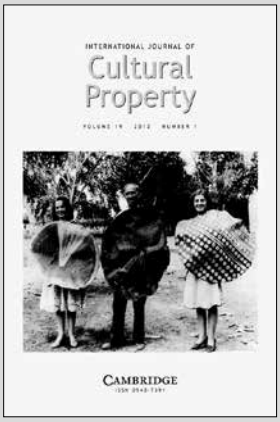


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