

# *How did we get opaque windows? - Mutual constitution of technology and the built environment*

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# How Did We Get Opaque Windows? – Mutual Constitution of Technology and the Built Environment

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## Abstract

Construction professionals are continually faced with the challenge of incorporating new technology into their buildings. Much of the current research treats innovations as a discrete entity, thereby overlooking the system properties of many innovations. Far from a bolt on process, implementation often involves extensive accommodation of both the technology and the building. Failure to appreciate this poses significant challenges to the project team, with unintended consequences for the project as a whole. A social construction of technology (SCOT) approach is used to explore the integration of Building Integrated Photovoltaic technology (BIPV) into three commercial projects. By exploring the succession of problems and solutions shaping the uptake of BIPV, the analysis also documents the mutual constitution of both the technology and the building in which it is located. The interest of BIPV lies in the bespoke, system nature of the innovation. Three decision modes are identified which help to explain how solutions can “lock in” features of either the technology or the building, often at the expense of the desired outcome. The research gives practical insights into how the incorporation of technology can shape the building into which it sits and how this processes occurs.

**Keywords:** BIPV, Projects, Innovation, Social Construction of Technology, Co-development

## 1. Introduction

Construction professionals are continually faced with the challenge of incorporating new technology into their buildings. While much of the research into innovation treats technologies as self-contained entities which can be inserted directly into a building, experience suggests that the process is often much messier. This is especially the case with many of the recent renewable technologies which are systems with multiple components rather than single units. It can also be ascribed to the lack of fit between the requirements of the technology and standard building

designs and practice. Far from a bolt on process, implementation often involves extensive accommodation of both the technology and the building. Failure to appreciate this often poses significant challenges to the project team; decisions concerning a particular design feature in either the technology or the building often throw up new problems, with unintended consequences for the project goals and for the building as a whole. This paper explores these issues by focusing on the micro-level dynamics accompanying the incorporation of Building Integrated Photovoltaics (BIPV) into three building projects. In doing so, it documents the mutual constitution of the technology and the building.

The challenge of green building is often treated as a problem of project team integration, with the focus being on professionals and their procedures and competencies. While this view captures important issues, the focus on professional roles and formal procedures obscures the complex decision making processes which explain how and why challenges are met. In addition, it masks adjustments to both the innovation and the building which accommodation produces. Little attention is paid to how innovative technologies involving cross-disciplinary issues affect the building in which they sit and the processes by which they are installed. What is missing is an understanding of how these interdependencies and the ways they are accommodated come together to shape both the technology and the building.

BIPV offers an example of a technology which is integrated into a building during construction rather than being bolted on during construction.. As such, the incorporation of the technology necessarily involves extensive accommodation at many levels and in many different ways as it interfaces with different aspects of the project and its components. These accommodations can be in the form of technical adjustments or through changes to standard designs or ways of working. These technical/design and process/management issues are often treated as distinct and separate but in practice are interrelated.

This paper uses the Social Construction of Technology to explore the ongoing accommodation of both the BIPV technical system and the building. The advantage of this approach is that it draws attention to the succession of problems and solutions which constitute the construction process. By focusing on the actors and objects involved in successive accommodations, it highlights three distinct modes of decision making which inform the uptake of a system innovation at the level of construction projects.

## **2. Literature Review**

Much construction research looks at sector level and macro level innovation; in contrast, this paper focusses on the challenges at the project team level by exploring accommodations to both the innovation and its context as the innovation is implemented. In doing so the paper rejects the notion of linear models of innovation and uptake (Rothwell 1994) and the distinctions between invention, innovation and uptake (Rogers et al. 2001).

A number of papers develop the idea that the effect of innovations varies with the local context. In a well-known typology, Henderson and Clark (1990)distinguished between four types of

innovation, based on the relation of the innovation to the firm and its processes; These include: architectural, modular, incremental and radical innovation. Whereas Henderson and Clark focused on the effect of discrete innovations, Slaughter (1998) explores the impact of innovations which are more systemic in nature. Her research classifies innovations by their distance from current practice, and their links to other components and systems. She distinguishes between the discrete types of innovation outlined by Henderson and those which have system characteristics and which therefore require, coordination among the project team, special resources and greater levels of supervisory activity. In a parallel study, DuBois and Gadde (2002) contrast different type of construction contexts. Their largely conceptual paper distinguishes between tight and loosely coupled systems to explain differences between how innovation is accommodated at the project level and the firm level. The discussion which follows builds on these general arguments concerning variations in the effect of innovations on the local context, be it the building design or the processes through which it is developed and argues for the need to explore empirically the process of accommodation within the project as an innovation.

The relatively more recent advent of micro level socio-technical studies has contributed significantly to our understanding of innovation implementation in construction. Both Kjellberg (Kjellberg 2010) and Harty (Harty 2008) use ANT to explore the introduction of innovations at the project level. In a study of the introduction of 3D-CAD software, Harty introduced the concept of relative boundedness to highlight the way in which innovations often have spill over effects which go far beyond those intended or even anticipated. Harty's study acknowledged variations in actors understanding and thus use of a similar technology, and pointed towards exploration of changes to the technical features of either the innovation or the context as it is implemented.

An aspect of this problematic can be found in Kjellberg's (2010) study of the impact of a process innovation on the transformation of a warehouse. In his paper, Kjellberg documented the effect of implantation of a new warehousing system on the building design and the associated actors. While, Kjellberg's study focuses on the transformation of a system, rather than a technical innovation, his argument concerning the extent of accommodations which the new approach required and the import of local context can be extended to the uptake of green technology..

A common feature in all of these articles is that they treat the technical features of the innovation as fixed. By introducing a sharp distinction between innovation and implementation, their work obscures the ways in which innovation shapes and is shaped by its context and continues to evolve as it is adopted. Understanding this dynamic would allow greater understanding of the process of innovation uptake. The importance of micro-level events in shaping the development of a building can be found in Clegg and Kreiner's (2013) study of construction failure. In a study of investigations into the failure of concrete beams, the authors highlight the way in which building outcomes are shaped by the performance of a multiplicity of "little things"(Clegg & Kreiner 2013, p.262). Their focus on the micro-level occurrences which shape the uptake of a technical artefact resonates with this papers concern for the micro-dynamics of innovation uptake.

The analysis which follows contributes to these micro-level explorations of the accommodation of building project teams and building designs to the demands of new innovations. In contrast to

these studies, the study of BIPV pushes the general argument one step further by problematizing both the design of the technology and the building. More specifically, the research uses the Social Construction of Technology to explore the succession of micro-level decisions and accommodations which contributed to the mutual constitution of both the BIPV and the building.

### **3. Background**

BIPV is a form of photovoltaic technology which is integrated into the fabric of a building. The technology is not fixed in format and is typically bespoke in design. It consists of several components: the photovoltaic cells which are laminated into the façade/louvre glass, connectors and wiring which take the DC generated electricity from the cell to the invertors, invertors which convert the electricity to AC and an export system which exports surplus generated electricity to the grid. Each of these components have implications for the design of the BIPV and similarly the design of the building will dictate the number of cells used, their configuration, length and location of wiring, position of invertors etc. By considering BIPV as a whole set of components, it can be considered as a technological assemblage which interfaces with the rest of the building design. Conflicts and resolutions occur as the technology is accommodated within the design and construction of a building. For example, the PV panels have to be accommodated within the frames of the façade, the wiring has to be concealed within the building and the invertors and metering systems have to fit within both the building and the electrical arrangements of the building.

### **4. Research approach and method**

#### **Analysis**

Social Construction of Technology (SCOT) adopts a socio-technical approach to technological development. Analysis focuses on the networks of actors and objects which form around the specification of problems and solutions in the development of a new technology or, in this case, in the implementation of BIPV into a building ((Bijker 2009; Schweber & Harty 2010).

For the purposes of this paper, the approach allows for consideration of the way in which construction professionals deal with problems and their resolution without privileging or distinguishing between types of issues (technical, design or management) and taking into account the system properties of both the technology and the building. Although SCOT usually focuses on the development of a single technology, this paper extends the approach to explore the co-development of BIPV and the building in which it is introduced.

The case study, Future Green, is a commercial science centre which incorporates BIPV into the windows to meet its carbon reduction goals. It is one of three case studies in a larger research project; it was selected for this paper because it illustrates a variety of different processes. Data collection combined semi structured interviews and document analysis. The project was identified by the supplier of the PV panels and contact was first made with the project architect. Snowballing techniques were used to identify participants, until no new project members were

identified. In total 13 construction professionals were interviewed. The research received ethics approval from the University of Reading and was carried out in line with these requirements.

Thematic analysis using NVivo 10 focussed on identifying problems and solutions arising during the project. In addition, attention was paid to the way that this succession of problems and their resolution contributed to the co-development of the building and the BIPV technology. Diagrams to explore the sequence of problem and solutions throughout the build were drawn up and problem solving strategies were identified.

As a method, SCOT highlights specific decision-making processes and discrete events which affect the development of a technology; however, it is less good at identifying the effect of broader structural characteristics which shape the process (Klein & Kleinman, 2002). In the case study discussed below, the use of SCOT may have obscured issues of project organisation, path dependencies or management styles, which indirectly influenced particular decisions and thus the uptake and ongoing development of BIPV.

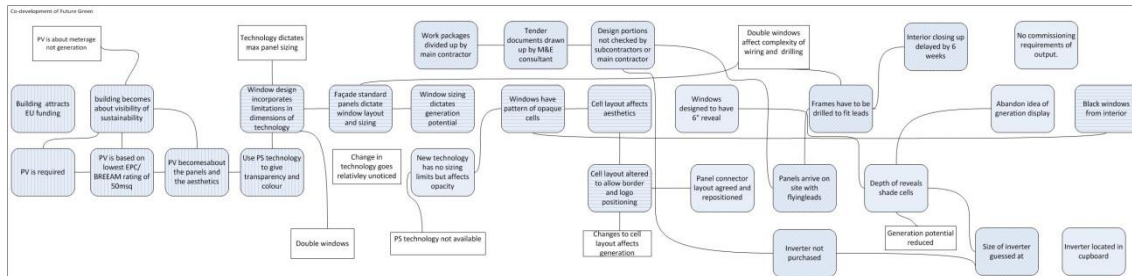
## 5. Future Green

The case study, Future Green, is a commercial science hub which is the first stage of a mixed development which includes the science hub, commercial offices, retail outlets and residential housing. The client group included a university and a city council, along with several other strategic partners. Future Green is a seven floor mixed space building, including exhibition and office space. Occupants, renting the offices are expected to be start-up businesses within the field of sustainability. Although predominantly council owned and run the building is operated by a private company which is in charge of letting space and running the building.

The project started out as a flagship sustainability project and BIPV was used to support this statement. BIPV panels were incorporated into ten of the 12 windows on the south-west elevation of the building. Other sustainable features included a small solar thermal installation on the roof of the building, a green roof and green wall on the west elevation and natural ventilation on the upper floors. The building includes many irregularly spaced, tall, narrow windows which make a bold architectural statement against gold cladding and green vertical brise-soleil panels. The project was a design and build contract.

The analysis which follows describes the co-development of the BIPV panels and the building, from the perspective of key design decisions and the socio-technical network which supported them. Figure 1 shows how the process of co-development occurred over the project and illustrates the key stages of the story. Each rounded, shaded box represents a decision or action which shaped either the building (the top line of boxes) or the BIPV (the bottom line). The unshaded square boxes mark key points in the co-development story. The four smaller sections of the diagram highlight particularly important parts of the development and structure the analysis of the mutual constitution of the building and the BIPV. The diagrams were derived from a SCOT framework of analysis which focussed on the problems experienced by the actors over the project and

identified the range of solutions used to resolve them. Enlarged sections of the diagram (e.g. figure 1) are used to illustrate specific points in the discussion which follows.



*Figure 1: Co-development of building and BIPV*

The integration of

BIPV is analysed as a succession of problems and solutions which led to the integration of BIPV within the window panes as a distinctive element of the glazing. Far from a simple decision, discussions around this feature passed through phases, each of which involved a slightly different problem and associated set of actors, objects and considerations. In the early stages, the architect proposed using thin film PV technology. During the tender phase, procurement problems led to their replacement conventional monocrystalline cells, but knock-on effects on frame design and glazing beads were not picked up until well into construction, resulting in delays and re-work. The traces this decision making process as it unfolded.

### Choice of technology

The clients were keen to attract European Regional Development Funding (ERDF)<sup>1</sup> for the project. To obtain the funding they had to achieve a BREEAM Excellent and preferably BREEAM Outstanding rating as well as an Energy Performance Certificate (EPC) rating of at least B and preferably A. Both EPC ratings required the use of renewable technology. Early on in the project, the client, architect and lead mechanical building services designer held a review of the sustainability options with a view to selecting which technologies to use. The architect and client became intent on using highly visible forms of sustainable technology so that future tenants and the general public would see that the building was green; they favoured the use of green walls and roof and solar technology (both solar thermal for hot water and photovoltaics (PV) for electricity generation). The design team considered using a conventional roof mounted PV system, but realised that the green roof would shade the panels. Instead, they suggested mounting them above the roof parapet, but this was rejected as it would not have been acceptable to the planners. In addition the PV panel frames would have had to be fixed to the roof, which would

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have necessitated piercing the green roof membrane and would have threatened water tightness. There was room for a small solar thermal installation on a separate part of the roof, but the space available was small and incompatible with a roof mounted PV system. Following these reflections the team decided to use BIPV.

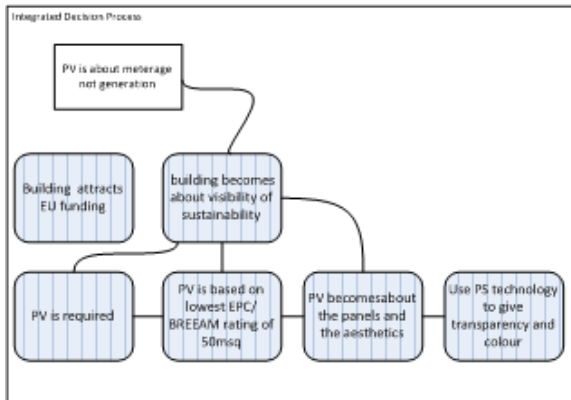
As indicated above, the decision to include a BIPV system was largely driven by the client's desire for a building with a strong sustainability statement. As the architect explained:

“...the only mandatory credit was the fact that we had to do this report. The PV itself as far as I know, we didn't get any extra credits for putting that in, in terms of the BREEAM... it was something we wanted architecturally as well, and it was specifically to get it integrated into the build, so it wasn't just a bolted on PV, it was integrated as the window system...Just in terms of the architecture, yeah, yeah. Just the look of the building”

Architect (NW01)

Under the initial proposal the building with BIPV was set to achieve BREEAM excellent and B for its EPC rating. For the reasons stated above, the client wanted an A rating. In response to this request, the mechanical design engineer performed the necessary calculations. He found that while only 50 sq meters of PV panels were required for a B rating, 260sq meters would be needed for the desired A result. The client decided that a B rating would be acceptable, but still wanted BIPV as part of the project. The architect wanted to incorporate BIPV on the large south-east elevation which was visible from the street. After looking at the building layout and the layout and positioning of brise-soleil louvres on the south east, the mechanical design engineer advised against this option as the façade had already been designed with large vertical brise-soleil louvres which would have shaded the panels and reduced efficiency. The two professionals toyed with the idea of incorporating the PV into the brise soleil louvres, but rejected this on cost grounds and eventually settled on using BIPV in the windows of the south-west elevation which had no brise-soleil fins. The architect decided to specify thin film PV technology which, despite being of a lower efficiency than conventional monocrystalline technology, would give some transparency to the windows and also allow the windows to be coloured bark brown and so add to the sense of drama and sustainability.

Figure 2 shows how the choice to use EU funding and the client's wish to make a strong visible sustainability statement drove the inclusion of BIPV on the project, which then moved the frame through which the actors viewed the technology from one of electricity generation to one of visibility. This drew the architect and designers to using BIPV in the windows and so made the choice of thin film technology desirable.



### Allocation of work packages

The process of developing tender packages for the project was also problematic. The project team continued to design the building, with the mechanical design engineers and architect developing the technical specifications and the main contractor deciding how the contracts for tender were to be allocated. When dividing up the work packages for tender the main contractor decided to include the BIPV panels in the envelope tender package and all the other parts of the BIPV system in the mechanical and electrical package for the internal work of the building.

“... it made perfect sense to us to put it into the envelope package, because like I said, it’s no different to installing any other window, it’s just got the PV components within it.”

Main Contractor (TH01)

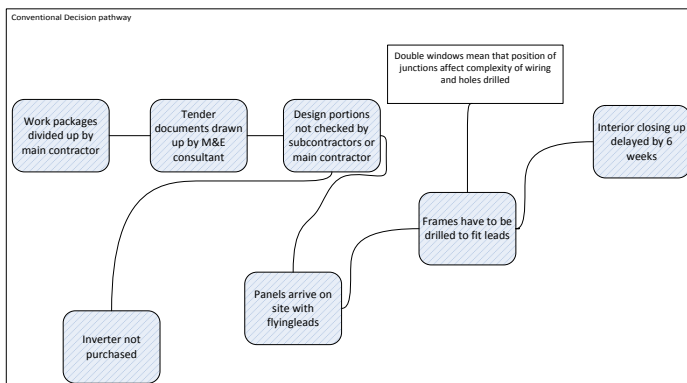
The M&E design consultants drew up the tender packages accordingly and included substantial design portions in each tender package for development of the design for the configuration of connections for the panels, location and sizing of the inverters and wiring from the panels to the inverters. The consultant was very clear that further integrated design between the M&E contractor and the façade supplier would be necessary to make the technology work.

“...they have to liaise quite closely with the architect over the installation details, because it would ultimately be part of the façade installation, the two would have to come together and form an integrated solution.”

Mechanical Design Engineer (SAW01)

The packages went out to tender and were duly awarded. The main contractor was not aware of the requirement for detail design of the system and the contractors had not read the detail of the specification. The façade supplier viewed the PV panels as just another sort of glazing panel and this resulted in the PV panels arriving on site with two flying leads on each panel and no plan about how they were to be incorporated into the façade and penetrate the building. Some windows were mounted one above the other and this double height design made the installation problems even more difficult. At the same time the M&E contractor had neglected to design how the wiring was to run from the frames and had forgotten to order the inverters. Figure 3 shows how this

progressive lack of integration and design eventually led to a delay of the internal finishing of that elevation of the building of six weeks.



### Change of technology

During the tender phase, the thin film technology was replaced by conventional crystalline cells as the original system proved to be unobtainable, but knock-on effects of this change on frame design and glazing beads were not picked up until well into construction, resulting in delays and re-work. The exterior of the finished building clearly showed the inclusion of BIPV in the windows, but internally this was translated into a loss of functionality – both in terms of the transparency of the windows and in the very small amount of electricity generated. As indicated above, the decision to use BIPV in the windows dictated the choice of thin film technology at the start of the project. This technology could achieve a blend of aesthetics and functionality. The brown colour of the panels would resemble wood bark and contrast with the gold façade while the semi-transparent finish would provide light through the windows. The thin film technology had limitations in terms of the dimensions that could be manufactured; this meant that most of the PV windows would be made from two panels, one above the other. In addition, the standard glazing panel sizing for non PV windows dictated the window layout and sizing. During the tender process the thin film technology became unobtainable and the supplier proposed to substitute it with conventional monocrystalline laminated PV panels which would provide slightly superior PV generation but which were much blockier in appearance. Transparency would be provided by the spacing between the PV cells, rather than as a general translucency across the whole panel. The architect and main contractor were keen to keep to the schedule and agreed that the new technology be used. The architect understood that the monocrystalline cells would affect the external appearance of the windows and worked with the glazing supplier to optimise the layout of the cells and logo to have an even border and symmetrical cell spacings. The architect was unfamiliar with the differences in the two technologies and summed up the situation as follows.

“The only difference as far as I know with that is it’s the graphical display of the cells... the original specification that we had was more of a bark wood type. ... it wasn’t a massive issue, we just went back to an alternative specification.”

Architect (NW01)

The knock on effects of this decision was that the changes to cell spacing affected the generation potential of the technology and the aesthetics of the windows from the inside. Instead of a semi-transparent brown wash, up to 80 % of each PV window now had blocks of black opaque cells. The other thing to pass without notice was that the restriction on the dimensions of the technology no longer applied, such that the windows could have been specified as one panel, thus reducing the number of joins and flying leads.

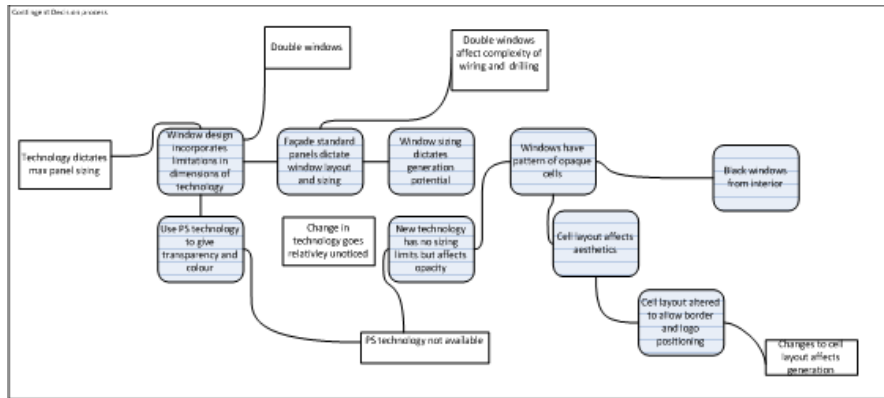


Figure 4: Change of technology

During the construction phase the lack of design and coordination of the BIPV system led to rapid decisions being taken over frame modifications, glazing beads and wiring configurations. These decisions sub-optimised the output potential of the system and resulted in delays and re-work. In addition, an aesthetic detail for deep window-reveals resulted in shadowing of the PV cells during significant periods of the day which dramatically reduced generation further.

## 6. Discussion: Modes of decision making

Over the course of the project a series (and sometimes parallel set) of problems and solutions led to the co-development of the building and the BIPV. The three sets of issues discussed above (and corresponding sections of the diagram) highlight three distinct modes of decision making, including: discrete decision making, conventional decision making and integrated decision making.

Discrete decision making occurs when decisions are taken in isolation without reference to the rest of the project. In this mode, decisions are made based on the immediate situation, where immediacy refers to both the spatial and temporal dimensions. In the decision over the choice of technology, the architect addressed the issue based on his aesthetic concerns. He selected the thin film technology because it gave a semi-transparent window and because its brown colour added to the sustainable look of the building. When the technology was no longer available from the original supplier, he agreed to substitute it with monocrystalline cells, without considering that the PV technology was only one part of the larger BIPV system. As the discussion above indicates, this discrete decision had a number of knock on effects. Not only was the generation capacity reduced, but the windows became opaque. Collateral damage also occurred when

original size limitations on the windows no longer applied, but were kept in the design, thus complicating wiring configurations and when the size of glazing beads needed were not altered to fit the new, thicker panels.

The term ‘conventional decision making’ refers to decisions based on standard procedures. Unlike discrete decision making, this mode takes into account broader temporal and spatial considerations, but not the specificity of the technology and the building. Like discrete decision making, this mode fails to take into account the knock on effects of the changes to components of the technical innovation. In the case of Future Green, this mode is evidenced in decisions around the procurement of technical components and the division of labour into work packages.

As the discussion above indicates, the main contractor divided up the tender work packages based on the conventional division between the envelope package and the internal mechanical and electrical fixing work. The M&E consultant was asked to draw up the work packages and allocated design portions within the packages. The result was that the visible aspects of BIPV were included in the envelope package, whilst the hidden part of the BIPV (the electrical part) was buried within the M&E package, where the design portion including sizing and procurement of the inverter was forgotten. Not only were the electrical components forgotten, but, also, the interfaces between the glazing units, the frames and the internal wiring were not considered until installation; consequent problems took six weeks to resolve.

The third mode identified in this study is integrated decision making. This involves collective consideration of the system properties of both BIPV and the building and is illustrated in the development of the initial bid for EDRF funding. In preparing the bid, the client, architect and M&E designer looked into the implications of using different forms of sustainable technology. They clarified the implications of installing a green roof and of using solar thermal installations and, based on these considerations, agreed to use BIPV on the façade instead of roof mounted PV panels. The decision to use BIPV in the windows was made once the requirements for an EPC rating of B were understood and the square meterage of PV matched the window sizing. The south west elevation was chosen for the BIPV as the implications of using the south east façade with its brise-soleil panels and consequent shading was unsuitable. All the team members were in agreement that BIPV windows were the preferred solution and understood that from that point the BIPV was primarily about making an external sustainability statement, rather than making a contribution to energy generation.

A second example of the integrated mode can be found in a coordinated response by multiple project team members to on-site problems. This type of flexible, local problem solving is widely recognised as a strength of the sector. In the case of Future Green, the conventional decision to separate the procurement of BIPV into mechanical and electrical packages and the subsequent isolation of the PV glazing from the frame led to a series of on-site issues ranging from how to incorporate the flying leads into the frame and take them inside the building to how to complete the weatherproofing of the envelope when the PV glazing beads were the wrong size. As the different subcontractors were brought together by the main contractor, an integrated decision mode was developed which allowed for innovative solutions to be found.

By analysing the use of these three decision making modes across the implementation process, it becomes easier to understand how and why problems arose in the incorporation of BIPV and why the project failed to deliver on its initial aims. Far from being unique to this project, the argument is that these dynamics are characteristic of innovation in the construction sector. In the case of Future Green, the integrated mode used at the beginning of the project allowed the team to focus on the issue of sustainability as a whole. This led to a holistic solution with clear specifications for the proposed BIPV system. When the thin film PV technology proved to be unavailable, the architect adopted a discrete decision making mode and agreed to the substitution of monocrystalline cell technology, without linking the decision back to issues of generation or functionality which stemmed from this decision. The main contractor's use of the conventional decision mode in deciding work package allocations set the scene for a fragmented development of the BIPV system and a series of problems at the interfaces of both the BIPV system and the contractors on site. Integrated decision making helped to address the local issues on site and encouraged some innovative problem solving, but it could not impact the effect of earlier discrete and conventional decision taking which locked in an opaque windows and low generation outputs from an early stage for the project. The "crown jewels" were indeed installed in an eye-catching setting, but despite good intentions, proved to be hollow when viewed from a point of functionality and value.

## **7. Concluding Comments**

In closing it seems incumbent to return to the initial research problem and ask what this analysis contributes to an understanding of technical innovation in general and sustainable innovation in particular. On one level, it documents the complexity of the decision making process and the co-development of system technologies and buildings. On another level, the distinction between modes of decision making provides the basis for a more nuanced understanding of how 'integration' might address the challenge of sustainable construction. Whereas most scholars focus on the integration of project teams, this study suggests that formal managerial changes are far from adequate. Instead, sustainable construction depends on a shift in the mode of decision making from discrete and conventional decisions which, while they have the benefit of efficiency, threaten to undermine client and project goals for the new technology. The challenge is for project teams to recognise the interfaces of the technology and identify which mode of decision making is most appropriate. In the study of innovation and uptake this raises the question: "under what condition do teams engage with an integrated mode of decision making and what can be done to encourage it?" It also raises the issue of the role of contracts/ and formal structures and procedures have in promoting conventional decision modes rather than integrated ones.

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