FROM BICYCLES TO BUILDINGS: A SCOT ANALYSIS OF PROJECT LEVEL ADOPTION OF BIPV

Thesis submitted in partial fulfilment of the requirements for the Degree of
Doctor of Philosophy at the

School of Construction Management and Engineering

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Dedication

For those who went before me, those who travelled with me and those who stopped to rest.

“All endings are also beginnings. We just don't know it at the time.”

Mitch Albom (2003)

Abstract

Building is consistently identified as one of the key sectors for sustainable development in general and for energy savings in particular (IPCC, 2007). The use of energy in buildings has been shown to account for around 40% of UK energy usage and improvements in building energy use and efficiency have become a significant focus of attention. This has resulted in the incorporation of innovative energy saving and renewable technologies into buildings. Worryingly, technological innovations for buildings consistently fail to deliver on their promises of improved efficiency and energy savings. There is a widespread assumption that the adoption of an innovative technology is mainly to do with the conditions of the market and technical effectiveness of the innovation. Given the complex nature of construction projects this assumption about adoption appears simplistic - many innovative technologies have to be accommodated within the fabric of the building and many project actors are involved in its incorporation. This research explores the process of building level adoption and asks what happens when an innovative integrated technology (BIPV) is incorporated into a building and in what ways this might explain the failure of the technology to deliver its potential. The research thus contributes to an understanding of the implications of the adoption of BIPV and other sustainable technologies in buildings. The Social Construction of Technology approach (SCOT) is used to study three UK commercial construction projects which include BIPV. Issues examined include: the changing interests of the actors; the network of problems and possible solutions; and the knock-on effects of the chosen solution on the rest of the project. The SCOT analysis of actors' interests and their changing relationship with the artefacts provides a way to explore the co-development of the technology and the building, and the adoption process. Interests of actors include: generation maximisation, aesthetic concerns, design optimisation and green guardianship. The SCOT approach is used to focus on design decisions taken over the course of the building project and the influence of different actor interests on these.

The research draws out different types of co-development and technology related decision-making which occurred during the projects and follows the effect these had on adoption. Rather than using formal roles (architect, designer, project manager etc.) and project stages (initial design, tender, detail design etc.) to explain adoption, the research found that the interests of the groups shifted and changed: sometimes they followed the standard project stages, but sometimes followed different logics. Decision-making was found to be affected by the alignment of technological frames being mobilised by actors and could be dominated by a particular frame at different times. It was not always the seemingly obvious groups which dominated decision-making and shaped the technology. The effect of social artefacts in decision-making was explored. This research develops an understanding of the dynamic process of adoption and concludes with practical implications for standard construction project procurement processes in the adoption of complex innovation.

Keywords: BIPV, Co-development, Social Construction of Technology, Innovation, Adoption, Project management, Performance Gap, Decision making

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It always seems impossible until it's done.

Nelson Mandela (1918-2013),

Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

The document has been proof read by a third party and I confirm that this has not compromised my authorship and that the substance of work has remained my own.

Philippa Boyd

April 2016

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Abbreviations and Glossary

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BIPV:	Building Integrated Photovoltaic
PV:	Photovoltaic
DC:	Direct Current
AC:	Alternating Current
BAPV:	Building Applied Photovoltaic
CSP:	Concentrated Solar Power
Wire:	DC wire used to connect panels to the inverter
Cable:	AC cable used to connect from the inverters to the mains
Inverter:	The device which converts DC current to AC current
DNO:	Distribution Network Operator
GW:	Gigawatts
FiT:	Feed in Tariff
RPI:	Retail Price Index
Merton Rule:	Camden Borough Council stipulated that new developments must generate at least 10% of their energy requirements from on-site renewable energy equipment
Part L:	Building Regulations Part L2a came into effect in the UK in 2014 and is designed to ensure that new non-domestic buildings deliver a 9% carbon dioxide saving
EPC:	Energy Performance Certificate

BREEAM Building Research Establishment Environmental Assessment Methodology - a method of assessing and certifying the sustainability of buildings by using a rating system to certify new buildings

SCOT: Social Construction of Technology

Interpretive Flexibility: the different meanings that one artefact may have for different groups of people

Technological Frame: the lens through which actors interpret the technology

RSG: Relevant Social Group

Stabilisation: the process by which the design of artefacts becomes more fixed

Closure: the mechanism by which the interpretive flexibility between groups decreases through negotiation and conflict

RIBA: Royal Institute of British Architects

Social Artefact: artefacts that are not present in a material form and are constructed as part of the project management process, rather than being part of the technology or the building for example a contract or schedule

Point of Friction: where the BIPV assemblage and building physically connected with part of the building also called friction interface

Inflection Point: when the frame mobilised by a project actor changed as the project moved from one formal project stage to another

Chapter 1: Introduction

1.1 Background to the research

New sustainable technologies are increasingly included on building projects to reduce energy consumption but the adoption of these technologies is complex. For sustainable technologies to make a real contribution to the reduction of energy consumption in buildings it is important that the process of their inclusion on building projects is understood. This research examines what happened on three commercial building projects as a sustainable technology was adopted.

Building is consistently identified as one of the key sectors for sustainable development (Parry et al. 2007) in general and for energy savings in particular. Buildings have been shown to account for around 40% of UK energy usage and around 33% of the greenhouse gas (GHG) emission (DECC 2014). Within the climate of national and international energy reduction agenda, improvements in building energy usage and efficiency have become a significant focus of attention for governments, practitioners and researchers. This importance has led to a raft of policies at all levels of government. In Europe, governments have been called upon to contribute to an overall reduction of GHG emissions by 20% and increase in energy efficiency and renewable energy each by 20%. Similarly, the (recast) 2010 Energy Performance of Buildings Directive (EPBD) calls on national governments to ensure that all new buildings are “nearly zero energy” by 2020. Both sets of goals depend on the incorporation of energy saving and renewable technologies into buildings. Photovoltaic technology has been deployed on over half a million buildings in the UK, with total installed capacity in 2018 set to exceed 4 Gigawatts (GW) (Department of Energy & Climate Change

2014). Building integrated photovoltaic technology (BIPV) is an example of a complex photovoltaic technology which is increasingly installed on commercial buildings and its adoption is an important part of energy reduction strategies. In 2011 installed global BIPV capacity was 1201 MW rising to 11,500 MW in 2015 (Renewable Energy World, 2011) and is projected to exceed 11 GW by 2020 (Global Industry Analysts 2015).

In the UK planning policies and building certification schemes have been put in place to promote the use of energy saving technologies in both domestic and commercial buildings. These policies, together with other factors such as improvements in technologies and an increased desire of firms to demonstrate a commitment to sustainability, have resulted in the increased use of renewable technologies in buildings. Commercial properties account for at least 10% of overall emissions and energy consumption, and clients for new commercial buildings are increasingly seeking to install new energy saving or generating technologies into the buildings. Technologies chosen can range from simple technologies like low energy lighting or roof mounted solar panels to more complex technologies like ground source heat pumps and building integrated photovoltaic systems which need to be integrated within the structure of the building.

These more integrated technologies are more than just bolt on, minor additions to the building structure. Instead these technologies have to be integrated within the fabric of the building itself and their incorporation is far from simple. This process of incorporation can require adjustments to the technology itself, the building into which it fits, and the standard design and construction stages which take place throughout a project. The resulting mutual articulation of technology, building and process can be thought of in terms of co-development and the way that this takes place shapes the resulting building design and electricity generation potential. BIPV is an integrated technology and the issues of integrating BIPV into a building are complex and affect many aspects of the construction process. Current research does not extend to understanding the project and process difficulties that arise when integrated technologies are incorporated within a building. Little research has been conducted into the micro-level occurrences which occur as a complex, integrated technology is adopted into a building project – both in terms of technical and social aspects. This research addresses that gap by exploring how decision-making evolves as successive problems and solutions unfold during the project level adoption of BIPV.

1.2 Research Problem

While much of the research into innovation and its adoption considers technologies to be self-contained entities which can be inserted directly into a building, practice suggests that the process is often much messier. This is especially the case with many of the recent renewable technologies which are integrated technologies with multiple inter-dependent components rather than single discrete components which require little integration.

Incorporation of these integrated technologies into buildings presents many challenges for construction in terms of technical performance, building development and project processes. Emerging reviews of the contribution of these technologies towards energy reduction targets consistently document a failure of the technologies to deliver on their promises of improved efficiency and energy savings (Leonard-Barton & Kraus, 1985; Palmer et al., 2016; Zgajewski, 2015). This would indicate that the process of incorporating integrated technologies within buildings is not straightforward and that for new technologies to deliver the required energy savings, a better understanding of the process of incorporating the product into projects is needed.

1.3 Aim and objectives

The aim of this research is to explore the micro-dynamics around the adoption of innovative technology and so develop an understanding of what happens when innovative, integrated technologies are incorporated into building projects. The research follows the inclusion of a new technology into three commercial building projects. Adoption is the term used to describe the process of incorporating the product into projects rather than the term diffusion which often refers to the spread of the technology once it is "market ready".

The research uses building integrated photovoltaic technology (BIPV) as an example of an integrated technology and examines what happened as BIPV was incorporated into three commercial buildings. It is concerned with the micro-level occurrences and accommodations that are made both to the innovative technology (in this case BIPV) and to its complex local physical and processual context during its adoption. This aim is supported by three objectives:

- To explore how the building and the technology develop as design decisions are made during the project when BIPV is incorporated;
- To examine what may influence the installed generation potential of the BIPV technology;
- To explore the implications of this research for the adoption of BIPV and other sustainable technologies.

1.4 Summary of research method

As the adoption process has both social and technical aspects, this research uses a social construction of technology approach (SCOT) to focus on the process of adoption as building integrated photovoltaic technology (BIPV) is incorporated within new buildings. The approach is used to examine how the co-development of the technology, building and project processes may explain this problem.

1.5 Synopsis of thesis

The integrated nature of BIPV is introduced in Chapter 2 with a description of the components within a BIPV system. Current research into the adoption of BIPV is shown to focus on the technical and commercial considerations of the technology, without looking at the micro-level issues surrounding its incorporation into a building. The chapter establishes that the practical challenges associated with the adoption of BIPV invite research to understand what actually happens when BIPV is specified on a building, thereby giving greater understanding of the process of adoption.

Current literature on the adoption of technology is explored in Chapter 3, together with a discussion about specific literature on the adoption of innovation in construction projects. Although some innovation diffusion studies recognise the effect that innovation has on its local context, they do not consider innovation adoption as a dynamic and two-way process. The chapter establishes that whilst barriers to innovation adoption have been extensively reviewed, little attention has been paid to the empirical study of what actually occurs on a construction project when an integrated new technology is introduced. Building on existing literature, the chapter develops the concept of the dynamic nature of innovation adoption and establishes that the study of the incorporation of an integrated technology within a construction project would provide insight into the dynamic process of adoption.

In Chapter 4, the Social Construction of Technology (SCOT) is established as the socio-technical lens to be used for this research. The chapter explores the use of this micro-level approach, which pays attention to the actors involved, the technology being used and the larger building project which accommodates it, to understand interdependent technical developments in a complex environment. For this study the relevant actors are the projects team members and the artefacts under consideration are the components of BIPV and the elements of the building with which they interface. SCOT is used to map out the unfolding series of problems and solutions which occur as the technology is incorporated into the building.

The research then explores the process of technology adoption by asking what accommodations are made both to the innovation and to its local physical and processual context during the adoption of an innovation. Chapter 5 sets out the design of the empirical research, which studies three commercial building projects each incorporating BIPV technology. Data from interviews and project documents is used to identify groups of actors who have different needs and expectations from the technology. The chapter then explores the successive problems and solutions which occur during each project as the BIPV system and the building develop. The ensuing mutual articulation of the building and technology is explored and is used to compare similarities and differences in the mechanisms of this co-development of building and technology on all three projects.

Chapters 6, 7 and 8 describe the case studies and analyse the key episodes in each of the projects in terms of technological frames and the co-development of the building and BIPV system. SCOT is used to explore how the project teams decided on which solutions to adopt for emerging problems and how this decision-making shaped the final configuration of the building and technology. Issues and challenges from the incorporation of BIPV that are particular to each project are examined and issues which have particular relevance for construction projects in general are identified.

Similarities and differences between the three case studies are examined in Chapter 9 and these are explored in terms of two key themes; integration and the dynamics of co-development. These themes are used understand some common mechanisms that were seen to occur during the adoption of the technology. Chapter 10 moves from an analysis of the three specific cases to a re-engagement with the literature on the adoption of technology. The discussion explores how the case of BIPV challenges a number of basic assumptions which inform research into innovation in general and sustainable innovation in particular. The chapter highlights how innovation occurs on-site as construction of the building proceeds and explores the implications of this in the adoption of integrated technologies.

Chapter 11 provides an overview of the research and presents its theoretical and methodological contributions. This chapter suggests implications for practitioners and proposes areas for further research directions. This research brings the dynamics of adoption into focus and allows for an understanding of how decisions are made and of the effects of those decisions on both the artefacts and the actors.

Chapter 2: Building Integrated Photovoltaic Technology

This chapter introduces renewable solar energy technologies in general and BIPV in particular, and describes the challenges associated with its adoption. The discussion introduces a key distinction between the adoption of complex, integrated technologies and the adoption of discrete, less complex innovations. This distinction draws attention to the multiplicity of decisions and considerations that occur in the adoption of these more complex technologies.

2.1 Renewable solar energy technologies

There are two main types of solar energy technologies: solar thermal energy (providing hot water) and photovoltaic power (providing electricity). Both of these types of solar energy make different contributions to the energy and carbon reduction agenda. The following section gives a brief introduction to solar thermal technologies and photovoltaic technologies and ends with an outline of BIPV technology.

2.1.1 Solar thermal technology

Solar thermal technology uses heat exchangers - usually mounted on the roof of buildings (either domestic or commercial), to convert heat from the sun into useable heat energy. Solar thermal installations are fitted after the roof has been constructed and are usually employed to heat the water used in the building, or occasionally to heat ceilings or floors. Solar energy is stored in the form of hot water and so can be used when there is no solar radiance. In addition to the panels on the roof (which are heat collectors) the assembly includes a heat transfer liquid (similar to a refrigerant), pipes to carry the heating medium to the hot water system, and a suitable water cylinder which uses a heat exchanger between the refrigerant and the hot water system to store heated water (eSolar et al., 2008).

Electricity is not generated by this form of solar technology and so considerations of connectivity to the electricity grid are not relevant. The exception to this is Concentrated Solar Power (CSP), when huge solar collectors are used within a power plant to heat water to become steam, which drives conventional turbines - so generating electricity. These power plants are generally geographically restricted to areas of high incident solar radiation (for example, Spain, Morocco, India and North America) (Khanna, 2012).

2.1.2 **Photovoltaic technology (PV)**

Photovoltaic technology uses a solar cells and wiring to produce electricity. The solar cells are usually embedded within solar panels and positioned to catch the sun’s rays. PV systems use a suite of technologies to convert solar radiation into electricity using the photovoltaic effect within a solar cell. Incident sunlight causes electrons to be energised within the cell, with the subsequent reactions generating an electromotive force, some of which is converted into electric energy. PV systems produce direct current (DC) and the power produced fluctuates with the intensity of the sun. It is not necessary to have full sunlight to produce electricity, but the angle of the cells and their orientation are important factors in maximising the potential electricity production.

Solar power assemblies consist of the PV cells, the matrix - usually glass, in which they are embedded (the panels), cables which carry the DC power, inverters which convert the DC electricity to alternating current (AC), and cabling from the inverters to the standard supply metering system. The electricity can be used to power the building where it is installed or can be exported to the grid. Any PV system in the UK which is connected to the grid attracts a

Feed-in-Tariff (FiT) for any electricity that is generated, which is paid by the local electricity supply company to the owner of the PV system.

There are two main ways in which photovoltaic systems are installed: building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV). The technologies remain similar, but the challenges of their installation differ greatly (Holden & Abhilash, 2014). Figure 2-1 gives a schematic representation of renewable solar technologies.

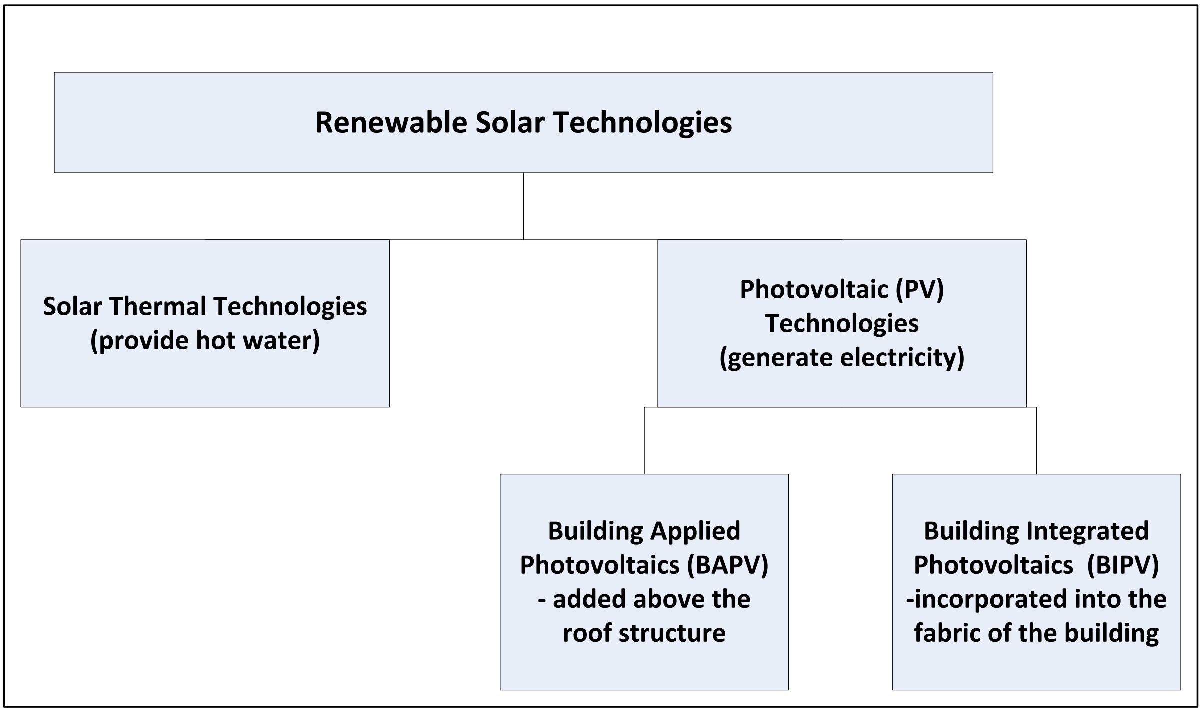


Figure 2-1: Renewable solar technologies

2.2 Building applied photovoltaics (BAPV)

Building Applied Photovoltaics are usually situated on roofs of buildings. The PV cells are mounted on top of the roof membrane and are not part of the structural element of the building. Panels are aligned to maximise incident light - the angle (azimuth) and direction of the cells - are optimised and the wiring and inverters are installed within the building. As the panels sit on the roof, often on a framework, there is little impact on the building structure and so BAPV is often installed as a retro-fit technology to existing buildings. The major challenge for this technology is to maximise generation from the number and position of the panels and to minimise efficiency losses from cable runs by siting the inverter as close to the panels as possible. Contracts for BAPV installation are often turn-key and generally regarded as an add-on to the main design and construction of the building (Holden & Abhilash, 2014).

2.3 Building integrated photovoltaics (BIPV)

BIPV is very similar to BAPV in terms of its components, but the key distinction is that with BIPV the photovoltaic panels are integrated into the fabric of the building, rather than being placed on top of the structure. This integration into the building structure can include using BIPV in the roofs, windows, façades, louvres, brise-soleil or rain screens. With BIPV, the panels replace conventional building materials in part of the building - for example roof tiles, façade panels or window glass. The function of the panels is a combination of electricity generation, architectural aesthetic appeal and building function (in terms of water tightness, strength, durability etc.).

Unlike BAPV, BIPV has many interfaces with the rest of the building structure, which makes it both expensive (by virtue of its bespoke nature) and complicated (because of the number and type of interfaces with the building) (Henemann, 2008). BIPV is generally restricted to commercial building projects, where each building is uniquely designed and where the adaptability of BIPV installations allows the technology to fit and contribute to the building architecture. The bespoke nature of the technology and the knock-on effects of its incorporation into a building project pose major challenges for construction professionals.

Figure 2-2 shows an example where BIPV has been used as part of the façade and roof of the building and demonstrates the combination of aesthetic and functional qualities of BIPV in buildings.

Figure 2-2: An example of BIPV

2.4 Component parts of photovoltaic systems

Rather than being a simple technology, BIPV systems comprise several component parts which have to be matched as a system and then accommodated within the design of a building. These component parts include photovoltaic cells, PV panels, wiring, inverters and meters. A brief discussion of each component serves to demonstrate the way that these components are inter-dependent and highlights the complexity of BIPV systems.

2.4.1 **Photovoltaic cells**

Photovoltaic cells are the components which convert photon energy into DC electricity. There are two main technologies commonly used: thin film and crystalline silicon. Much research is being invested in developing newer and more flexible spray-coated technologies, but these are still in their infancy (Zweibel, 1999).

Thin film technology involves thin layers of a photovoltaic material being deposited directly onto a substrate (glass, plastic or metal). The technology is cheaper than its crystalline counterpart, but is less efficient in terms of electricity generation. The production of thin film technology is fast and more efficient and longer lasting films are increasingly available. An additional advantage of thin film technology is that the degree of opacity can be manipulated to allow a significant degree of transparency for daylight transmission (Razykov et al., 2011).

Crystalline silicon technology involves either growing or casting ingots of silicon crystals which are then sliced into wafers. Each wafer is termed a PV cell and is shaped and polished. Electrical contacts are deposited onto the cells so that they can be connected together. Figure 2-3 illustrates a single monocrystalline PV cell with wiring strips.

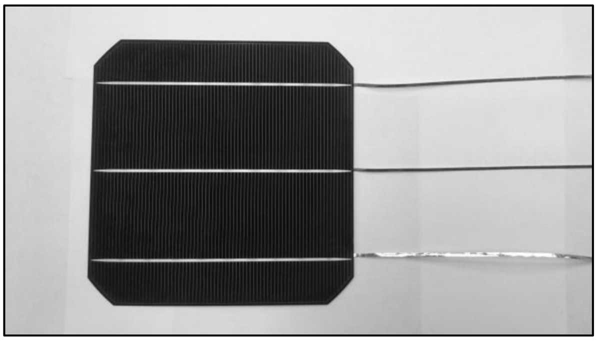


Figure 2-3: PV monocrystalline cell

The method of manufacture determines whether a homogenous crystalline framework is produced as a bar (monocrystalline) or whether the matrix consists of small crystals (polycrystalline) (Solar Cell Forum, 2016). These methods of manufacture are standard across the world, with the largest manufacturing country being China. There is a trade-off between cost (monocrystalline is more expensive than polycrystalline), and generating efficiency (monocrystalline is 14-19% efficient while polycrystalline is only 11-15% efficient).

2.4.2 **PV Panels**

The PV panel is the substrate in which the individual solar cells are fixed. Solar cells are arranged on a substrate - often by hand, and connected together with thin, (usually) tin-coated copper strips. A slightly larger thin strip is positioned to collect the output from the cells and two connectors are positioned to allow panels to be connected together. Once the layout is complete, the cells are sandwiched between sheets of glass and are annealed. This produces a rigid, laminate panel which can be used as a building material. Figure 2-4 shows PV cells laid out on the glass substrate prior to laminating the glass layers.

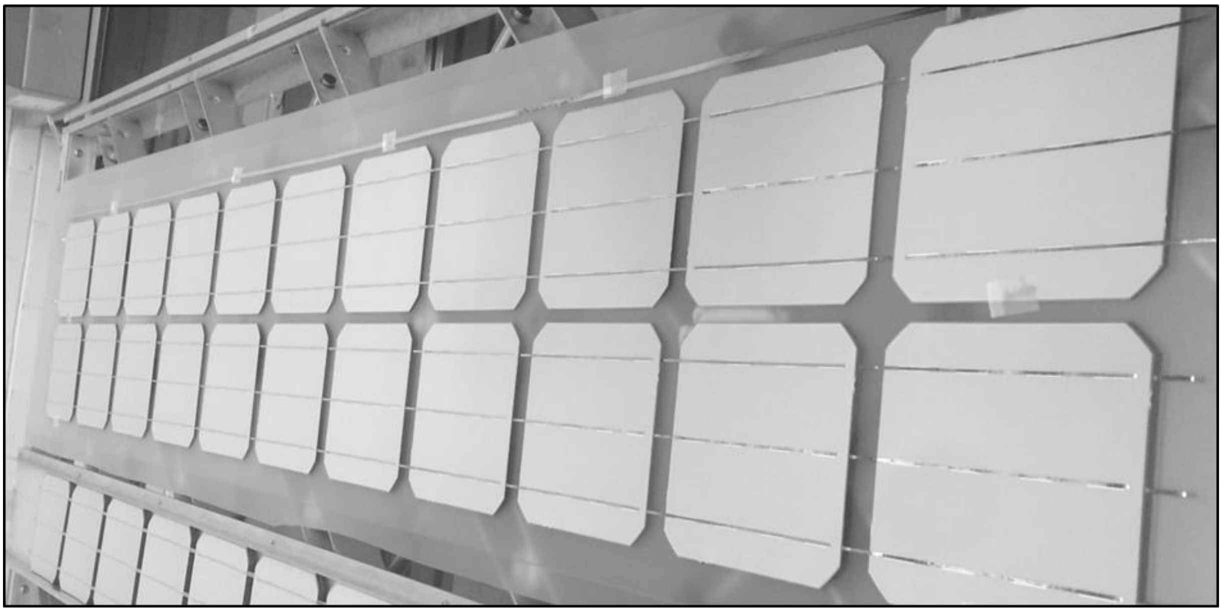


Figure 2-4: PV cells laid out on glass laminate

2.4.3 **PV system wiring**

Wiring for PV panels has to be matched to the system being installed in terms of the DC voltage being generated, the length of the cable run and the acceptable percentage loss.

Typically cables are heavy duty, flexible rubber-coated and vary in diameter from 1.5mm to 400mm depending on the voltage generated (Energy Development Co-operative Ltd, 2013). Each PV panel has to be connected together and the configuration of this wiring determines the characteristics of the system. There are three major considerations: the order in which the cells are connected; the specification of the wiring used; and the distance over which the wiring has to run before it is connected to the inverters.

PV panels can be connected together in two main ways - in series or in parallel. The choice depends on whether the installer desires either increased current or increased voltage. In the case of parallel installations, each positive terminal is connected together and each negative terminal is connected together. This configuration (shown in Figure 2-5) gives more current and allows more efficient inverters to be used.

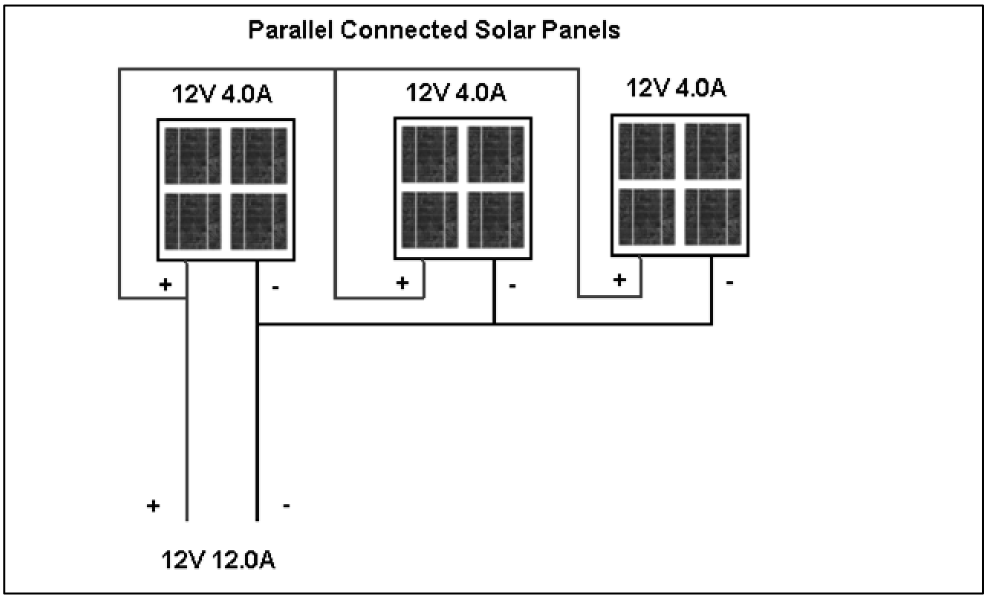


Figure 2-5: Parallel connection of PV panels (Save the polar, 2013)

In the case of series connection, the positive terminal of one panel is connected to the negative terminal of the next panel and so on along the string of panels. This configuration

(Figure 2-6) increases the voltage output from the system, but has the disadvantage that if one panel in the series or string fails then generation from the whole string is lost.

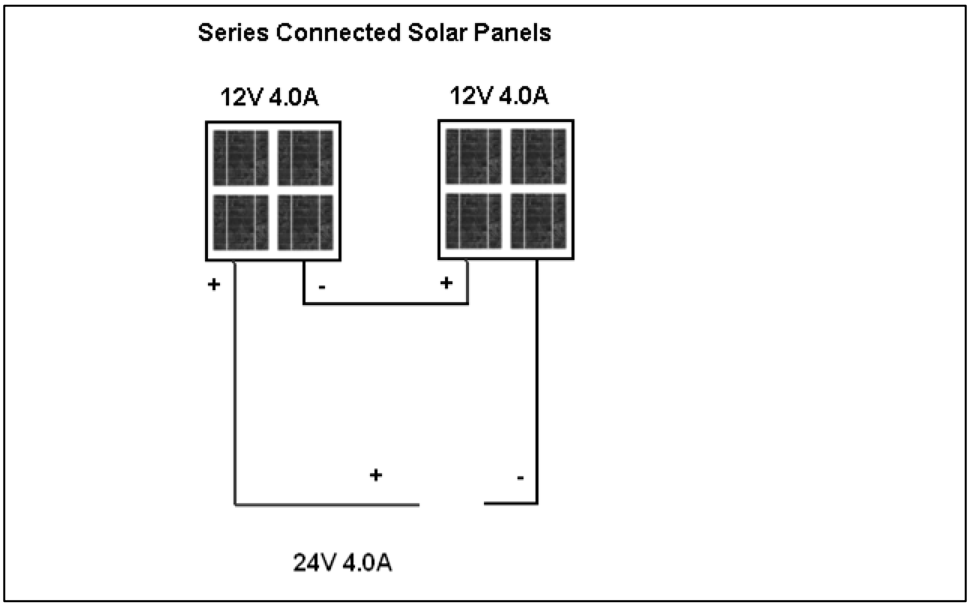


Figure 2-6: Series connection of PV panels (Save the polar, 2013)

Generally in BIPV systems, panels are connected in series as a string. Each string of panels is connected to other strings in parallel and these parallel strings of panels are used to increase both the current and voltage generated by the system. This configuration also reduces the risk of failure of the whole system from either shading or maintenance issues as each string generates electricity independently from the others. Figure 2-7 illustrates how this arrangement of panels is configured. This configuration of panels can give rise to bulky wiring runs, as each string has two sets of wires which have to be routed to the inverter (BRE et al., 2002).

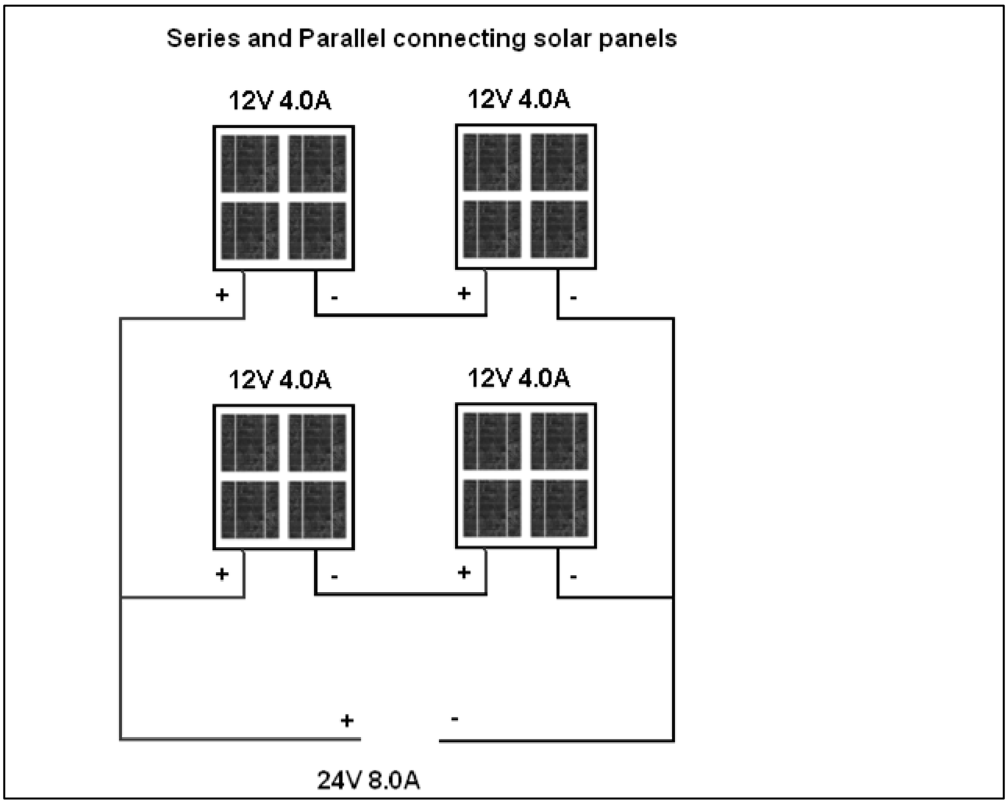


Figure 2-7: Series and parallel connection of PV panels (Save the polar, 2013)

Different wires have different resistance characteristics and this affects the efficiency of the system. Larger diameter wires generally offer less resistance to the current and are considered more efficient. Resistance is also affected by the material of construction of the wire and recent technical developments have made available lower resistance, smaller diameter wiring. When considering BIPV, there is usually a trade-off between the cost of the wiring and the space taken up by the wiring (BRE et al., 2002).

The length of the wiring run from panels to inverters influences the resistance of the wiring and therefore the efficiency of the system. The efficiency losses increase with the length of wiring runs and it is therefore better to keep wiring distances as short as possible (BRE et al., 2002).

2.4.4 PV system inverters

Inverters are used to convert DC current to AC current and so make the electricity generated from the cells compatible with mains voltage. This compatibility allows the electricity generated by the PV panels to be joined to the mains electricity entering the building and used either within the building directly or else exported to the grid.

The number and type of inverters used in an installation depends on the number of panels used, the wiring configuration of the panels and the output voltage. String inverters are used to collect the outputs from several strings of panels (connected in series) whilst micro-inverters are attached to each panel. Both options have different costs and advantages. String inverters are cheaper and easier to install, whilst micro-inverters provide greater efficiencies, but are more costly and can require the installation of sub-collectors (BRE et al., 2002). Figure 2-8 illustrates a bank of inverters and isolators for a small BIPV installation.

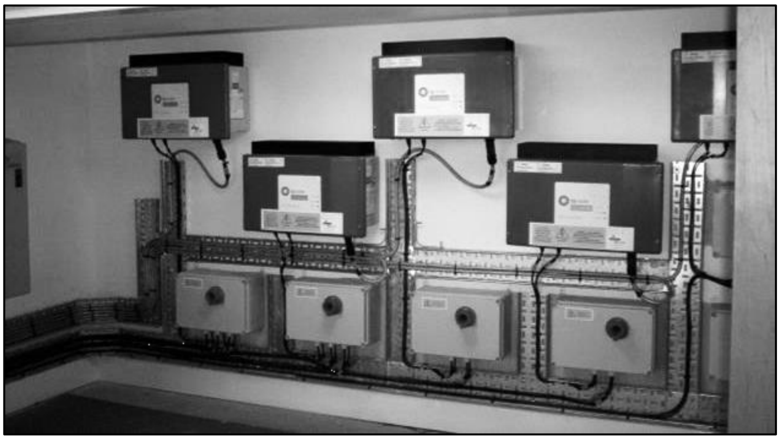


Figure 2-8: Inverters and isolators

2.4.5 Cables

Conventional AC cabling is required from the inverters to the G59 cabinet (see 2.4.6). These cables differ from the DC wiring as they carry electricity at higher voltage but lower current.

They are also typically larger in diameter than the DC wiring (BRE et al., 2002). The cables are sized to minimise voltage drop and to contribute to overall system efficiencies. Total system losses from electrical components can reach around 14% (BRE et al., 2002).

2.4.6 **G59 cabinet and isolator**

This part of the PV system takes the AC electricity from the inverter and allows it to be connected safely to the mains electricity entering the building. It is a UK standard requirement that the PV system be connected to a G59 device which is sited in a cabinet just before the isolator switches (BRE et al. 2002). The G59 is a mains protection relay and is programmed according to parameters fixed by the Distribution Network Operator (DNO). If the PV output falls outside these parameters (in terms of voltage, frequency or current) circuit breakers operate to isolate the system from the grid. Figure 2-9 shows an internal view of a typical G59 cabinet.

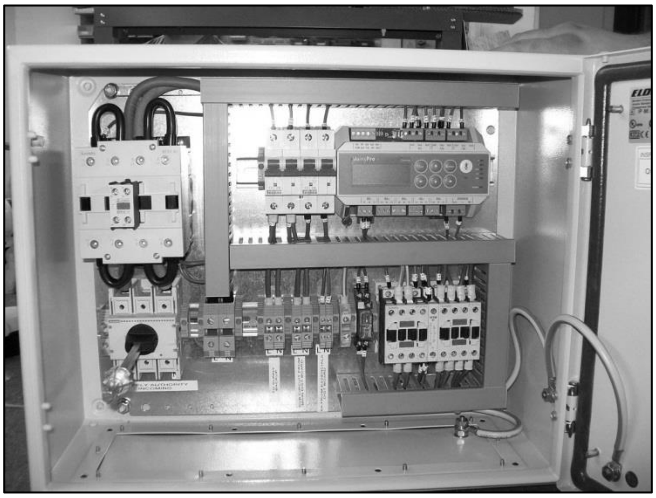


Figure 2-9: Typical G59 cabinet (Sibert Instruments, 2016)

This section has described the main components of a BIPV system with a view to giving background to the case studies in the dissertation. The discussion has highlighted some of the design considerations required for each component and has explained how the components are interconnected. It is this inter-connectivity of the BIPV system that makes its incorporation into buildings a significant challenge.

2.5 Diffusion of BIPV in the UK

There are a number of UK policies which affect the adoption of BIPV, but three in particular are important to this research and require a brief introduction. These policies are Feed-in Tariffs, local planning requirements and building certification schemes. Whilst not exhaustive, these policies provide an important context for the case studies presented later (Chapters 6, 7 & 8).

2.5.1 **Feed in Tariff (FiT)**

At the time of writing, all electricity generated in the UK by a PV system qualifies for a Feed in Tariff (FiT) payment. All generated electricity is metered and a generation tariff is payable for every kilowatt hour of electricity generated. In addition, if electricity is exported to the grid, an export tariff is payable for every kilowatt of electricity exported. Under current policy, Feed in Tariff is paid for a period of 20 years and is index linked to RPI.

2.5.2 **Planning requirements**

At the time of writing individual UK council planning requirements vary considerably. The use of renewable energy within buildings is often a condition of planning, as is the development of a sustainability strategy which sets out the way in which a building contributes to the UK Government’s low carbon agenda. For example, between 2003 and 2015 Camden Borough Council stipulated that all new non-residential developments must generate at least 10% of their energy requirements from on-site renewable energy equipment (Merton Council, 2015) and this policy directly affected one of the case studies. This policy has now been superseded by the new energy requirements in Part L2a Building Regulations 2013 - conservation of fuel and power in new buildings (HM Government 2006). Building Regulations Part L2a came into effect in the UK in 2014 and is designed to ensure that new non-domestic buildings deliver a 9% carbon dioxide saving and that this is demonstrated in the Energy Performance Certificate (EPC) for the building.

2.5.3 **Building Certification Schemes**

Local planning policy in the UK has increasingly required energy efficiency to be considered in new builds and this has focussed attention on the specification of renewable technologies and in particular BIPV. There has been a growing requirement from clients for building certification (e.g. LEED and BREEAM) and from the Government for energy performance certificates (EPCs), which has increased the specification of BIPV on buildings. Two of these certification schemes are of particular relevance to this dissertation and this discussion gives background information to support the case studies.

BREEAM (Building Research Establishment Environmental Assessment Methodology) is a method of assessing and certifying the sustainability of buildings by using a rating system to certify new buildings. Certification grades are Outstanding, Excellent, Very Good, Good and Pass. The scheme uses a system of credits in ten areas of sustainability and the use of sustainable technology is included within two of these areas. All three case studies were BREEAM Excellent buildings (BRE).

Energy Performance Certificates (EPCs) are required for non-domestic buildings constructed after 2008 (DCLG). Buildings are rated for their energy efficiency on a scale from “A” to “G”. Renewable technologies make a contribution to the energy efficiency of a building and the use of BIPV on the case studies used was a contributing factor to the buildings achieving the higher energy performance certification levels of “A” or “B”.

2.5.4 **BIPV systems in UK buildings**

BIPV technology has been commercially available in the UK since the 1990s and has been increasingly used in flagship commercial builds. The technology is expensive but provides a very visible demonstration of green credentials. BIPV projects in the UK are custom designed for each application - there are no “off the peg” solutions.

Exemplar BIPV projects in the UK have included:

- Heron Tower, London, a 46 storey building with 4000m^2 of PV modules integrated into the façade, which generate 92,000kWh of electricity annually. The panels meet 2.5% of the building’s electricity demand.
- Blackfriars Station, London where BIPV roof panels were installed as part of the station refurbishment. The 1.1 MW system spans the River Thames and is expected to generate 900,000kWh per year, which is 50% of the station’s electricity requirements.
- Kings Cross Railway station, London where 1,392 laminate roof panels covering 2,300 m^2 of have been installed to generate 175,000kWh electricity annually

2.6 Research into the adoption of BIPV

In view of the generic challenges posed by BIPV and the particular issues regarding adoption discussed above, it is somewhat surprising to find that there has been little research into the process of adoption for BIPV. Current literature on BIPV focuses on three main areas: technical challenges of the technology, ways to improve its market diffusion and industry advice to professionals on BIPV installation.

Research into the technical challenges of the technology tends to focus on the formal features of the technology and its anticipated impact on energy use. Much research is highly technical, concentrating on scientific advances and improvements to the system. At a less technological and more performance-based level, issues studied include system performance (Sozer & Elnimeiri, 2007), reliability (Laird, 2009) and cost (El Chaar et al., 2011). What this research has in common is the shared assumption that once the product is technically sound and economically viable, adoption will surely follow.

Alternative and perhaps more balanced views of the adoption of BIPV consider ways to improve market diffusion by identifying barriers and enablers for the adoption of BIPV. Barriers to adoption have both technical and non-technical elements. Research into non-technical barriers is generally concerned with sustainable technology as a whole, rather than BIPV as a particular technology. Barriers have been found to include issues of sustainable policy, regulation and economic incentives (Tsoutsos & Stamboulis, 2005), the need for project team integration and supply chain integration for sustainable construction (Mollaoglu-Korkmaz, S., Swarup, L., and Riley, D., 2013; Yang & Zou, 2015) and the need for early involvement of specialist engineers in the design process (Specialist Engineering Alliance, 2009). Whilst these issues are important, research into non-technical barriers for adoption tends to be very general and ignore the differences across technologies and buildings. Technical barriers for the adoption of BIPV have been found to include issues such as: structural compliance; system design; electrical safety; and calibration (Yang, R., 2015). These technical barriers to adoption indicate that the issues of integrating BIPV into a building are complex and affect all aspects of the construction process. However, research does not extend to understanding the project and process difficulties that arise when BIPV is incorporated within a building.

Literature from the photovoltaic industry (for example BRE, National Solar Centre, CIBSE, solar panel suppliers) includes guides to size and design systems, advice on building certification and Feed in Tariffs, and recommendations for project teams (BRE et al., 2002). These guides tend to be of a prescriptive nature, setting out guidelines for best practice without necessarily appreciating the constraints of construction projects and the practicality of the guidance. Curiously these industry guidance notes assume an idealised world, where communication between contractors is clear, where there is continuity of personnel and where system design parameters are well defined. As the following case studies will show (Chapters 6, 7 & 8) this is not necessarily the reality of construction projects.

Research into the adoption of BIPV focusses on the technical and commercial considerations of the technology, without looking at the practical issues surrounding its incorporation into a building. The interrelationships between the technology, the physical building and the project team interactions around these are a critical issue in the adoption of BIPV, and this mutual articulation is under-represented in the literature and typically over-simplified. What is missing from research currently is an understanding of how the specification of BIPV in a project poses considerable challenges both for the project team and for its integration into the building. In particular, this gap invites research into how decision-making evolves as successive problems and solutions unfold during the adoption of complex, integrated technologies.

2.7 Challenges of BIPV adoption

The incorporation of BIPV into a new building poses four technical challenges: the unique configuration of the technology for each building; the frequent changes made to the technology; the integration of the technology within the building; and the fit with standard procedures and processes. A discussion of each of these challenges establishes the basis for an understanding of the issues posed by the technology and for the complexity of the case study analyses presented later.

From the descriptions earlier in the chapter, it is clear that BIPV comprises many components, each of which brings its own characteristics and challenges. What is less immediately obvious, but presents one of the major challenges for the project team, is that the BIPV system is uniquely configured for each building. The decision to include BIPV may be relatively lightly taken, but the design of the technical elements is complex.

A further challenge of BIPV is that the technology changes rapidly. Initially available PV cell technology can be superseded by improvements in design and efficiency over the course of a project. Changes to inverter design can involve smaller, more efficient units, often fewer in number, requiring different connection strategies. Wiring and cabling developments can mean that cables become thinner and connectors differently configured. These rapid developments have two implications. First, construction projects take years to design and often longer to build. The BIPV design proposed at the start of the project is likely to include technology that is outdated and perhaps more expensive than the technology that is available at the installation stage. Secondly, changes to safety standards and procedures are fast changing and can themselves impose changes to the BIPV system being designed.

The third and arguably the greatest challenge for the construction industry is that the BIPV system has to be integrated within the building. As an integrated technology, BIPV has to be designed to fit in with the aesthetic considerations of the building, be strong enough to form part of the building structure and be functional enough to perform the duty of a window, roof or louvre. As well as these requirements for a flexible but functional system, all the elements of the technology have to be accommodated within the building design. Panels have to be mounted within the façade and the wiring has to be integrated within the structure of the building so that it does not detract from the aesthetics or functionality of the design. The control system has to connect to the building's main electrical design. At the same time, the size of the wiring and the length of wiring runs have to be optimised to reduce system losses, and be invisible. Inverters and G59 cabinets have to be accommodated within the building, must be sized to minimise losses and need to be connected into the main electrical systems of the building. All of these considerations make the integration of a BIPV system into a building a complex process which is intertwined with the design of the building itself.

Finally, the design, installation and commissioning of the BIPV system has to fit within complex and well established project procedures and practices. For example, as the case studies which follow indicate, these procedures and practices are not necessarily designed to adapt to new technologies and the inclusion of BIPV might lead to problems and tensions over the course of a project.

In summary, the adoption of BIPV is complicated by its many inter-related components, the need to incorporate an assemblage of technically diverse components into a building (which is a complex assemblage in itself) and the pre-existing procedures and processes which are used in construction projects. These challenges invite research to understand what actually happens when BIPV is specified on a building and thus give greater understanding of the process of adoption. The next chapter reviews literature which deals both with the adoption of technology and also specifically with the adoption of innovation in construction projects.

Chapter 3: The Adoption of Innovative Technologies in Buildings

This research is concerned with the adoption of sustainable technology in buildings. Chapter 1 established the background and importance of this topic in terms of the climate change agenda and UK policy. The UK Energy White Paper (2007), Climate Change Act (2008), and Energy Bill (1998) have had the effect of raising the profile of the energy performance of buildings and have influenced the development of planning regulations and building certification schemes. Two particular schemes have been developed from these policies to increase the adoption of sustainable technologies. Firstly the EU Energy Policy Buildings Directive (2010) requires all new buildings to display an energy performance certificate (EPC) which gives an assessment of the building’s energy efficiency. Second the voluntary BREEAM certification scheme (BRE, 2015) is adopted by building owners as a way of demonstrating their commitment to sustainability and of adding value to the property. Both certification schemes are aimed at increasing the adoption of sustainable technologies in buildings but there is increasing research which suggests that while certification can provide a means of recognition and increased reputational value for buildings, their effect on the adoption of sustainable technology in buildings varies. Schweber and Haraglu (2014) used a comparative case study of eight building projects to identify variations in the effect of BREEAM on design decisions within projects and the impact of these decisions on sustainable construction. The authors found that the level of adoption of sustainable solutions depended more on the project actors’ individual engagement with sustainability issues, rather than knowledge of individual technologies or of the BREEAM method. This gap between intent and effect of policies and certification tools has been observed at many levels. In a review of the composition and nature of sustainable development indicators Russell and Thomson (2009) conducted a review of government documents, comparing the vision of a sustainability strategy for Scotland with the operationalisation of that policy in terms of sustainability indicators. They found that there was significant misalignment between the objectives of sustainability policy strategy and the effect of sustainability indicators used to achieve these objectives. Although neither of the research above was aimed specifically at matching sustainable building certification to the adoption of sustainable technology, both indicate that the way that strategy and schemes are operationalised does not necessarily achieve the desired outcome of increased adoption of sustainable technology.

Much literature on innovation and its diffusion assumes that adoption will follow once the technology is commercialised and economic conditions are met. This assumption is particularly striking in the literature of the performance gap which explores the difference between the “boiler plate” design potential of technology and its installed performance (this difference in performance is often called the “performance gap”). This literature starts from the assumption that technology and buildings should perform the way that they are modelled or designed. Performance gap studies (Fedoruk et al., 2015; Zgajewski, 2015) show that despite the technology being readily available, technological innovations for sustainable energy in buildings consistently fail to deliver on their promise of improved efficiency and energy savings. This signals the need to gain a better understanding of the processes which occur during the adoption of technology and the resulting adaptations which might affect the performance of the technology and the building.

Much of the research concerned with innovation adoption focusses on developing models which are held to be a universal description of the adoption or innovation process, and on specifying best practice (Tidd, 2001). The question which the models generally address is: can the adoption of innovation be modelled, predicted or improved? These models range from simple linear S-curve models (Ryan & Gross, 1943; Rogers, 1976) to more complex models which involve iterations and parallel working, to models of integrated innovation and adotpion (Mensch et al., 1980; Rothwell, 1994). Of their time, these models gave ground-breaking insights into the field of innovation adoption, but generally addressed simple product innovation which proceeded in a linear manner through simplified stages of market need, development, manufacturing and sales. These simple block models, albeit with the later addition of iterative feedback loops (Rothwell, 1994; Aranda-Mena et al., 2008) assume idealised communication networks, processes and relationships, and treat these as general, universal stages which apply to all innovation adoption. In his latest retrospective on diffusion work, Rogers himself stressed the emerging importance of networks and the effects of sociological interactions (Rogers, 2004) and in this way signalled the need to understand what is happening in respect of the innovation and its local context.

In research adoption of innovation is often considered from two opposite points of view: from the view of the innovation or from the point of view of the user or adopter of the innovation. The former point of view looks at the technology, models its development and diffusion, examines the barriers and enablers to make adoption occur or explores how improvements and developments of the technology encourage adoption (Pagliaro et al. 2010; de Wilde 2014). Research from the other view examines innovation from the user end and seeks to understand why the user adopts the innovation, the impact the innovation has on the user (its characteristics) and how the user can adapt the innovation to suit their required purpose (Menezes et al., 2012; Fedoruk et al., 2015). Whilst both these viewpoints of the adoption of innovation are important, it is a third view of adoption of innovation which is of particular relevance to this research and moves away from the generic towards a more specific understanding of the adoption of technology. The process view of innovation seeks to understand the processes of adaptation which occur as an innovation is adopted (Van de Ven et al., 1989). This exploration of the intermediate processes which occur as an innovation is adopted is important in the context of construction projects where an innovation is specified on a project and must then be incorporated into a building before being handed over to the user or client.

This literature review starts by exploring research into technical approaches to innovation adoption and the performance gap and establishes the need to understand more than just the technological development of the innovation. Using literature which shows the effect of the adoption of innovation on its local context, the review then establishes a link with literature on the process of innovation. By outlining six themes of innovation adoption within process innovation research, the review then goes on to develop connections with literature on the adoption of innovation in construction projects. The review concludes by establishing the importance of developing a socio-technical understanding of understanding the project and process difficulties that arise when new technology is incorporated within a building. This review establishes the paucity of research on the process of innovation adoption and proposes empirical research to explore the process of incorporating innovative technologies into building projects.

3.1 Technical approaches to the adoption of innovation

Although seemingly technology and context specific (with a focus on energy and buildings), the concept of the performance gap (the gap between the predicted performance of a technology as designed and the performance in use) can be used to explore issues within the adoption process. Research into the performance gap can be divided into three categories: work on the modelling of energy performance (de Wilde, 2014; Menezes et al., 2012), work on building occupants and the effect of their behaviour on energy performance in use

(Sunikka-Blank & Galvin, 2012; Rohracher & Ornetzeder, 2002) and a third small but growing literature on the role of building delivery in the 'gap' (Dainty et al., 2013; Gorse et al., 2012). It is this third category of research which gives insights into the intermediate process of innovation adoption outlined above.

Literature which addresses the role of building delivery in the performance gap points to issues within the adoption process which should be considered. Gorse et al. (2012) built on research which established the evidence of performance gaps in wall cavity insulation (Lowe et al., 2007), to document and explain possible reasons for this gap. A post-occupancy survey of twenty five houses compared designed thermal performance figures with measured heat loss data, and used interviews and technical reports to identify themes which might explain the differences. The conclusions indicated that much of the measured performance gap stemmed from poor understanding by the construction team and mistakes in installation which were not picked up during the commissioning process. The other striking conclusion of Gorse et al.'s research was that very few buildings are routinely checked for performance and compliance with design figures. Although a small survey, it points to issues in adoption which are more than just technology related and this finding is supported by other researchers. Dainty et al. (2013) conducted a largely review-based study of contextual factors which affect performance of low carbon technologies in housing and identified similar issues in the performance gap and the need for performance evaluation. In addition they developed a model for a collaborative approach between all parties in the supply chain to deliver good building performance. Fedoruk et al. (2015) studied the construction of a sustainable university building and its performance testing and concluded that attention should be focussed on measuring and publicising performance characteristics as a means of improving adoption.

What these studies have in common is that they recognise that the adoption of new technology is not a simple process which is concerned with improvements to technology. Instead the research draws attention to more processual elements of innovation adoption which occur during construction projects and show that these may account for issues of performance gap.

3.1.1 How context of adoption influences the technology

The performance gap literature discussed above gives a view that technology is influenced by its context during the adoption process – for example that the thermal performance of cavity walls is influenced by the quality of workmanship during construction (Gorse et al., 2012), or that project processes of supply chain management and performance testing influence the performance of low carbon technologies (Dainty et al., 2013). This view signals a departure from empirical modelling of innovation and its adoption which assumes that the innovation once "market ready" remains relatively stable during adoption. Empirical modelling of adoption is usually limited to a single innovation adopted within a specific, simplified market or sector - such as integration of "Just-in-Time" management within the car industry (Rothwell, 1994) or the adoption of BIM within construction contracts (Aranda-Mena et al., 2008). Such research does not address the way that the innovation changes through the adoption process; rather it assumes that innovation of a product is an iterative process which ends prior to adoption. In other words, once the technical properties of the technology are established, the main challenge is the market (Rogers et al., 2001). Many innovative technologies are not clearly bounded, stable products, but are complex in nature, requiring integration into their local context. In construction projects this local context is both the material building which accommodates the innovative technology and the social element of project team processes which are used to deliver the building with the new technology incorporated). As such, product development extends well into the implementation phase and affects both the technology (the BIPV) and the context into which it is introduced (the building and the project processes). It is this interplay of accommodations and development which needs to be explored.

3.1.2 How the adoption of technology influences its local context

The idea that innovation can shape its local context is developed in literature which explores the effect of innovation on its local context. This understanding adoption of innovation gives a richer, less technological understanding of some of the issues of the adoption process. The view that innovation has different characteristics which have different effects on its local context was developed by Nelson and Winter (1977) and developed further by Tushman and Anderson (1986) who used data from the mini-computer, cement and airline industries to examine patterns of technological change. They proposed that innovation could be assigned either competence enhancing properties (incremental innovation) or competence destroying properties (radical innovation) to innovations, and this pointed to differences in how the local context responded to the innovation. The typification of innovation by its effect was developed further by Abernathy and Clark (1985), who used examples from the US automotive industry to develop the concept of incremental change as a more organic and enhancing innovation model, which was occasionally disrupted by radical innovation (often from sources external to the firm). These radical innovations had the potential to endanger existing business models and allow new entrants to the field. The more benign incremental innovations continued profitably for existing players whilst radical innovation heralded change and threats to the status quo. It is this understanding that innovation can affect and change its local context which indicates that the adoption of innovation is a complex process.

Henderson and Clark (1990) questioned the universality of the radical and incremental categorisations, by looking at how individual firms accommodated technological innovations within existing products, and developed a more nuanced understanding of the effects of the innovation on its local context. Their research in 1990 developed a distinction between four types of innovation: architectural; modular; incremental; and radical, each of which had a particular effect on the firm into which it was introduced. In simple terms, incremental innovation could be thought of as renovation or simple improvements to core components which have no effect on the local context. Modular innovation could be described as replacement of part of a technology with new components which fit into the existing system without needing excessive changes. Architectural innovations need to be accommodated by changes to existing technical and organisational processes, whilst radical innovations signal a major departure from the status quo.

When translated into the context of a construction project the implications that technological innovation has different characteristics which shape its local context become significant. Construction projects involve temporary teams made up of many different firms, using different processes and involve millions of components and technologies. The challenges of construction projects and their management in terms of adoption of innovation are discussed in section 3.3.1, but it is clear that the adoption of new technology into building projects will also have effects on the management of the project and on the constitution of the building itself. It shows that the process of adoption is more than a simple stage of innovation diffusion and underlines the dynamic nature of the process of adoption as both the innovation and its local context are affected.

This review of literature has so far shown that the process of adoption of innovation is more complex than stage models would suggest. Performance gap literature has established the relevance of considering adoption from a process viewpoint and the link has been made between the complexity of integrated technological innovation and the ongoing process of accommodation as the technology is incorporated. The dynamic nature of innovation adoption has been demonstrated by literature which shows the effect of innovation on its local context and vice versa. The section has demonstrated that technical performance and the characteristics of the technology are not sufficient to understand the adoption of integrated technologies, and that a more processual understanding of the process of adoption is needed. Pettigrew (1985) and Van de Venn (1986) developed a processual view of management and innovation which can be used to consider the adoption of technology.

3.2 Processual view of innovation adoption

The processual view of innovation builds on an approach to the management of strategy and organisations. Processual views of innovation explore how and why innovations develop over time from concept to implementation, and seek to understand how an innovation (either technical or processual) comes into use. Process research was rooted in the development of organisation change theory and practice (Pettigrew, 1985; 1990), where longitudinal studies into organisational change management were conducted and a process approach was used to draw out theories of change management to help business managers understand and implement change. By applying the approach researchers use detailed empirical study of the actors involved in the change and the study the sequence of events which occur over the length of the change project. Pettigrew (1985) put forward the idea that strategic management rarely follows the ideal of rational decision making and planned change. The epistemological approach of process research has been used to study innovation by exploring the development of innovative businesses (Van de Ven, 1986; Poole, et al., 2000). Process innovation research is directed towards assisting project managers to understand the emergence and development processes of innovation and to see that innovation comes about through “complex and meandering processes” (Sminia, 2009. p.98). This processual view of innovation can be seen to inform an understanding of the adoption of an integrated technology into a construction project.

Process research has developed three main ways of looking at “process”: as a logic where a particular outcome is defined by different variables; as a series of steps which can be modelled as a series of cause and effect variables; and as a pattern of developmental events which unfold as a change occurs (Poole et al. 2000), This third strand of process research recognises that the phenomenon being studied changes through the innovation period and uses a longitudinal study approach to explore behavioural response to events rather than the research object itself (Pettigrew 1990). Longitudinal, qualitative research into empirical case studies is used to understand the critical events which occur and the causal patterns which take place in the development and implementation of new ideas (Pettigrew, 1985; Van de Ven et al., 2008). Seeking to help managers of innovation to manage the innovation process, these studies propose a process road map of the innovation journey. In particular the Minnesota innovation research project (MIRP) (Van de Ven & Poole 1990) used longitudinal studies of innovation to explain how and why innovations develop over time. These empirical cases were used to observe change, code and analyse event data to identify process patterns which could explain the observed innovation processes (Van de Ven & Poole 1990). Van de Ven et al.’s process model (2008) was developed from studies of specific innovations and identifies three common phases within the innovation process: the initiation period; the development period; and the implementation/termination period. It is the last of these elements which is directly relevant to the study of adoption of innovation. In developing a process view of the adoption or implementation of innovation, Van de Ven et al (2008) identify several key characteristics of the implementation/termination period which include: setbacks occurring frequently; shifting innovation performance criteria; fluid participation of innovation personnel; top management involvement and roles; the frequent altering of relationships; and the creation of a community and infrastructure. Generally research into process innovation focusses on developing skills for managers when implementing innovations within organisations and on how to manage these problems effectively, but does not explore the effects of the process of innovation on the team, the business into which it is introduced or the innovation itself. Although the focus of process innovation research on the managerial and social aspects of innovation excludes consideration of the effect of the process of adoption on the technology, it does suggest that these themes will have an impact on the development of the innovation itself and they will be revisited in section 3.3 with a particular focus on construction research.

A review of literature on the innovation process by Garud (2013) concluded that innovation is "not just the emergence of a new idea or a final product, but the entire process that takes an idea from inception to implementation" (Garud, 2013, p.803). He also observed that "innovation processes unfold not just within firms, but also across multi-party networks, and within communities" (Garud, 2013. p.803). This particularly resonates with the context of construction projects which have just such complex interdependencies (section 3.3.1). This draws attention to the complexity of innovation adoption and in terms of the adoption of integrated technologies like BIPV, provides a point of departure for further empirical research of specific innovations to understand more about what happens when an innovation is adopted.

Process innovation research gives a view of common patterns which occur in the adoption of change in strategic management. These patterns were described as: leadership; changing relationships; infrastructure; learning; and change and adaptions (Pettigrew 1985). Van de Ven et al.'s (1989) later research into the process of innovation refined these descriptions into six themes of the implementation/termination period and named the themes as: setbacks occurring frequently; shifting innovation performance criteria; fluid participation of innovation personnel; top management involvement and roles; frequently alteration of relationships; and the creation of a community and infrastructure. Section 3.3 will show how these themes point to issues which are also identified in construction management literature and the section highlights some common challenges in the adoption of innovation.

Process innovation research (Van de Ven et al., 1989; Pettigrew, 1990) compares empirical, longitudinal case studies to show common patterns emerging between the cases and to demonstrate the complex landscape of innovation adoption. This comparison of cases allows researchers to develop managerial or organisational understandings of the process of innovation. This element of comparison is central to exploring common elements of the non-linear, but also non-random process of innovation and will be used in the research design to reflect on the process of adoption of BIPV in buildings.

3.3 Six processual themes of innovation adoption in the context of construction projects

The six themes of the implementation/termination period which were identified by Van de Ven et al (2008) during the Minnesota Innovation Research Project (MIRP) (setbacks occurring frequently; shifting innovation performance criteria; fluid participation of innovation personnel; top management involvement and roles; frequently alteration of relationships; and the creation of a community and infrastructure) resonate with many challenges already identified within a range of construction management literatures. The following section place the contribution of process innovation research into the context of that literature.

An important focus of innovation research within construction is concerned with understanding the context within which construction projects are carried out (Pavitt, 1984; Malerba, 2002). The setbacks which occur frequently in construction projects occur during the processes of project management, change management and decision making (Salter and Gann, 2000; Cooke-Davis, 2002; Chinowsky et al., 2008; Bakht & El-Diraby, 2015). These management themes have their own literatures and are discussed in section 3.3.2. Shifting performance criteria are evidenced throughout construction projects (Gorse et al., 2012; Dainty et al., 2013), where new requirements are brought into projects at different points in the project by different actors. For example, the project manager may be concerned with achieving the lowest price on a contract at one point, but may then focus on making up project time at another. These shifts in focus and attention of the project team actors have been shown to affect the performance of innovation and technology and are discussed in the section 3.3.3. The observations of process innovation research on the fluid participation of innovation personnel resonate particularly with the temporary and evolving nature of project teams (Sexton & Barrett, 2003; Harty, 2008a) which is discussed in section 3.3.1. Much construction management research focusses on the effective management of project teams (Salter and Gann, 2000; Bourne, 2001; Cooke-Davis, 2002) and section 3.3.4 discusses the links between this and the observations in process innovation. Process innovation research makes much of the role of the leader and indeed one of its major concerns is to equip managers with tools to lead effectively. Construction management research also has a focus on leadership (Huber, 1991; Cohen & Levinthal, 2012) and one strand of this literature is particularly concerned with capabilities of firms to lead innovation and the role of the innovation champion (Nam and Tatum, 1997; Gambatese and Hollowell, 2011). This literature is discussed in section 3.3.5. The final characteristic identified by process innovation research is that of the creation of an infrastructure surrounding the innovation. Each construction project has a unique infrastructure which includes clients, contractors, subcontractors and users. The complex inter-organisational nature of the project team and the supply chain and its impact on innovation management has been recognised with construction literature (Dubois and Gadde, 2010; Bresnen & Marshall, 2000; Briscoe et al., 2001; Briscoe & Dainty, 2005) and this relationship is expanded in section 3.3.6.

Translated into construction management literature on innovation, the common themes of process innovation in the implementation/termination period have resonance with a range of construction innovation literatures in terms of the management of projects, change and decision making; the shifting of performance criteria of within projects; the temporary and evolving nature of project teams; leadership of innovation; and managing the inter-organisational relationships within the project - particularly with respect to the supply chain. The following section looks at the nature of construction projects and then reviews literatures which reflect the themes above within the context of construction, with a view to exploring both the processual and material elements of innovation adoption.

3.3.1 The nature of construction projects and implications for adoption of innovation

Construction projects have the distinctive characteristic of being both fragmented and systemic. Their systemic nature comes from the number and interdependence of firms and actors involved in project procurement, ranging from architects, main contractors, and specialist consultants, to suppliers, designers and subcontractors. The fragmented nature of construction is a result of the highly specialised and diverse nature of the projects it delivers.

Rather than being a stable, cohesive unit, construction projects involve temporary, multi-disciplinary, multi-firm projects teams, with different firms within a project having different priorities and sensitivities (Pavitt, 1984; Malerba, 2002). Membership of the project team changes during the course of a construction project, with actors joining and leaving the team at different stages. For example, it is normal for the main contractor's firm to change its representative during different stages of the project, so the project manager at concept design is likely to be a different project manager to the one at detail design and different again during mobilisation and construction (JCT, 2011). The supply chain of a construction project has a complicated series of relationships and obligations which are typically bound through complex contractual arrangements (Sinclair, 2012). Firms within the supply chain serve the main contractor or supplier, but also have their own ways of workings and their own alliances and interests. Within the formal project arrangements and interdependencies, there are informal systems, relationships and procedures which further fragment the project team.

These characteristics, coupled with both formal and informal systems, relationships and procedures, make the process of adoption of innovation in construction complicated. Winch (2003) contested the conventional view that the construction industry lags behind other industries (in this case the motor industry) in innovation adoption. He asserted that the construction sector does adopt innovation but that the complicated supply chain dynamics mask the adoption of innovation. A micro-level exploration of the adoption of innovation within a building project would test this assertion.

In an attempt to understand better the adoption process within construction projects, and in particular to do this with regard to more integrated innovations, Slaughter (1998) examined the impact of innovations which are integrated in character. Building on the concepts of incremental, radical, modular and architectural innovation (Nelson & Winter, 1977; Tushman

& Anderson, 1986; Henderson & Clark, 1990), Slaughter proposed that innovations could be differentiated by their degree of change from current practice and their links to other parts of the building assemblage. Slaughter distinguished between the discrete types of innovation outlined by Henderson and Clark, and those which have system characteristics and which require timing of commitment, coordination among the project team, special resources, and a high level of supervisory activity. Slaughter then used her largely synthesised framework, which categorised system innovation within the construction industry, to simulate and assess the impact of innovation within a project and then to suggest strategies to increase the efficiency of innovation adoption (2000). Although this later predictive work did not address empirical details of the effects of innovation in depth, her work contributed to the understanding that the complex nature of project work complicates innovation adoption.

Having established the characteristics of construction projects and the impact that these characteristics have on innovation adoption, the next section of this review examines literature which links some of the complexities of adoption across the construction project with the themes which emerge from the processual approach to innovation described in section 2.2.

3.3.2 **The management of projects, change and decisions**

This section considers the management of projects, change and decision making, in terms of project practices, processes and procedures. Construction teams do not operate in a vacuum; they are composed of multi-disciplinary, multi-firm team members who are primarily accountable to a parent firm, but who also have strong project allegiances and responsibilities. This duality of responsibility makes the adoption of innovation potentially problematic, as project team members may not be free to adopt innovative technologies, procedures or processes unless these are in line with their firms' policies and procedures. Salter and Gann (2000) explored factors which inhibited innovation and its adoption in construction projects. In an interview-based comparison of project based firms, they identified potential mismatches in business and project processes which inhibited innovation adoption and learning across the organisation. These differences signalled a disparity between business processes which privilege standardisation of systems and project based goals of flexibility and adaptability. In the context of the adoption of BIPV, this would indicate that there is a tension for the project team between existing project processes and the adoption of new procedures or procedures which might simplify adoption.

It is important to recognise that a building is not a fixed, static object into which an innovation has to fit; instead it is a complex assemblage of systems which must be managed and coordinated by the project team. Façade systems, lighting systems, heating and ventilation equipment, etc. all have to be designed, procured and installed with reference to each other, and there are established project processes to manage these.

Construction projects are governed by standard procedures and practices, both in terms of the stages at which project team members engage with the project and the procedures that are used to manage the project (JCT, 2011). The project specific nature of construction and the existence of complex procurement processes mean that contracts and their management are an important element of innovation and adoption. There have been consistent calls for the development of clear contracts with more collaborative approaches and clearly understood project requirements, rights and obligations, together with early involvement of the whole construction team (Bourne, 2001). Questions that these issues raise are about how contracts are drawn up when integrated technologies are used; how change orders are handled; and what this means for the project in terms of adoption of innovation. The discussion which follows looks at research which addresses these questions.

Ideals of project management include timely work package definition and tender, increased collaboration and continuity, and a fixed project schedule (Cooke-Davis, 2002). This has been followed by attempts to understand better the impact of construction processes on adoption of innovation and the commitment of resources needed to assist this (Slaughter, 2010a; Slaughter, 2010b). In particular Slaughter (2010a) noted that attention should be paid at the initiation of the project to the implications of innovation on the project supply chain and that integrated technologies need to be taken into account very early on in the development of the project. Gruneberg et al. (2007) suggested that performance-based contracting (PBC) could be used to ensure that innovative technologies were procured and installed in a way that delivered the intended benefits of the innovation. Whilst seeming to represent good practice, this early involvement of the supply chain, and timely consideration of the implications of innovative technology within a project, appears to be in tension with the current predetermined and habitual project management processes and procedures.

Change Management

A further example of tension between standard project management practice and the adoption of innovation is in the context of project change management. Change orders in construction projects are used to control deviations from the detail design of a project. They are generally raised to amend design or installation details and often involve re-work, wastage and cost. Project managers try to minimise their use, unless responsibility for the changes and payment is negotiated (Love and Li, 2000; Sun and Meng, 2009). Shipton et al. (2014) explored the effect of this resistance to change orders and noted that concerns about the following of procedure and the minimisation of change took precedence over acceptance that change might be required in order to improve the functionality of the building. Innovation adoption in construction projects is likely to result in change which will have substantial knock-on effects. In simple contexts, change is bounded in the firm within which it is adopted and repercussions outside the firm are small. Within the more complex context of construction, there are a series of loose and tight couplings which mean that predicting the knock-on effects of even small changes is unpredictable and often unexpected (Dubois & Gadde, 2010; Harty, 2008). This “domino effect” of change implies that innovation does not stop at specification, but continues, often in unplanned directions during adoption. The idea that adoption is a process which takes place during implementation can be found in Clegg and Kreiner’s (2013) study of construction failure. Their research analyses an investigation into the failure of concrete beams and highlights the way in which building outcomes are shaped by a multiplicity of “little things” (Clegg & Kreiner 2013, p263). Their focus on the micro-level occurrences which shape the adoption of a technical artefact (object) resonates with the idea that micro-level explorations of the accommodation of building project teams and building designs to the demands of new innovations will inform our understanding of the dynamics of innovation adoption.

Decision making

The process innovation view of this aspect of innovation recognises that many changes occur during the course of the implementation of an innovation and that the management of setbacks is of particular importance (Van de Ven et al., 1989). These studies recognise the snowballing effect of setbacks, as the consequences of one decision lead to a build-up of effects which are difficult to manage. However the studies do not look at either how decisions are made or what impact these decisions have on the innovations. To address these ideas of decision making it is useful to consider particular literature on decision making within construction.

Decision making literature within construction falls into three main groups: the development of tools for decision making; the identification of key decision makers and groups , and the development of techniques for decision taking (Krishnan et al. 2001). This research into innovation adoption is not concerned with quantitative methods to optimise decision making tools, but is concerned with understanding: who takes decisions; on what basis; and with what result. As concerns for sustainability within the built environment become more important, the criteria used for decision making have become more complex. How project teams balance criteria for decision making will directly affect the outcome of the project and will have an impact on the technology and building.

Increasingly research recognises that decisions within construction projects are taken with the involvement of many team members and in the context of a social network, as well as having a technical element. This social network approach to decision making takes a step back from optimising decision making in terms of project management efficiency and recognises the key roles of individuals within project networks and the complexity of communication that transpires (Chinowsky et al., 2008; Bakht & El-Diraby, 2015). Social Network Analysis is used to improve project outcomes by modelling the network of decision-making during a construction project, identifying key project actors and the categories of decisions taken (Keast & Hampson 2007a). Whilst this network approach identifies characteristics of effective networks and suggests best practice for project decision making, it does not go further into identifying the impact that decisions have on the development of the technology or building.

The last contribution of decision-making literature is on identifying how decisions are made – judgement based , rational based or emergent (where the final consensus arises as a result of interactions among multiple decision contributors) (Bakht & El-Diraby, 2015). Empirical research on this aspect of decision making is mainly limited to decision making within single firms over the course of product innovation (Krishnan et al. 2001), but Taylor and Levitt (2007) identify the need to understand the dynamics of decision making in innovation that take place in complex project networks.

It would seem from this review of decision making that although the concept of multiple stakeholder decision making and the complex criteria for taking decisions are well identified, there is a paucity of empirical research which identifies the effects of decision making on the innovation itself. Given the preceding discussion of the performance gap in section 3.1, this is perhaps surprising.

3.3.3 **Shifting performance criteria**

Within process innovation literature Van de Venn et al. (2008) identify three types of outcome criteria that run through the implementation phase of innovations. These were defined as Input Criteria (resources needed, time required, information needed etc.), Process Criteria (technical milestones, budget and schedule deadlines, credibility etc.) and Output Criteria (demonstrate success, contribute to goals, growth). This research illustrates that these criteria do not operate in practise in the rational, linear manner described in project management literatures, but operate in a sometimes divergent manner which leads to periods where criteria shift as different information becomes available. The focus of the process innovation approach is to highlight the problems created for project managers by these shifting criteria, but it is axiomatic that shifting criteria will affect how decisions are taken in the course of a project and that these decision chains will affect the materiality of the innovation and its context.

Something of the shifting criteria at play in the construction of buildings is evidenced by Gorse et al. (2012) in their exploration of the performance gap in cavity-wall insulation and by Dainty et al.'s (2013) review-based study of contextual factors which affect performance of low carbon technologies in housing (these are discussed more fully in the performance gap section of this review). The conclusions of these papers indicate that that output criteria in terms of project success are considered in terms of project completion schedules, budgets and client satisfaction and that the focus of the project team changes as the project proceeds.

3.3.4 **The temporary and evolving nature of project teams**

Process Innovation literature identifies that the temporary and evolving nature of project teams brings some advantages to projects in terms of new perspectives and competencies, but also identifies issues with loss of information, expertise and common purpose. These contributions to project management literature are largely in the form of suggestions for improved project team performance but, from the discussions above, will have a large effect on the decisions made, the criteria adopted and ultimately on the performance and configuration of the innovation itself.

3.3.5 **Leadership of innovation**

Angle and Van de Ven (1989) identified four counterbalancing roles of leadership within the innovation journey which did not reflect personal characteristics of one project team member, but which were shared among decision making executives, leaders and managers. They went on to identify that disagreement between these decision makers acts as a series of checks and balances during the innovation project. This perspective on leadership from process innovation research is very different from other research into innovation leadership which focusses on the importance of a particular role of innovation champion or sponsor (expanded below). By recognising that innovation leadership is an interdependent set of roles, the approach shows that decisions are made pragmatically in response to changing conditions and the differing perspectives held by other top managers, rather than by planned course of action. These insights raise questions for the adoption of innovation in the autonomous and highly networked forms of construction projects where work is carried out away from hierarchical environment of parent organisations. They also invite reflections – particularly in terms of technological innovation - on where leadership comes from in a project, who makes decisions in projects and what concerns or criteria frame their decisions.

Within literature which focusses on the role of innovation leaders and the particular importance of the innovation champion, different views are prevalent. The link between innovation diffusion and the capability and knowledge of those involved in its adoption has been well established (Utterback & Abernathy, 1975). Firm level capabilities to assimilate innovation (Cohen & Levinthal, 2012) and knowledge transfer capabilities within firms (Huber, 1991) have been shown to have important effects on innovation diffusion, but a study of these organisational aspects of innovation adoption falls outside the scope of this dissertation. What is within the scope of a more micro-level understanding of innovation adoption is the role of the innovation champion. During a study of the relationship between types of leadership and successful innovation, Nam and Tatum (1997) conducted over ninety interviews with construction professionals to identify key aspects of innovation leadership. They surmised that one of the key characteristics of successful innovation was the presence of an innovation champion, who would follow or push the adoption of innovation.

Nam and Tatum suggested that this champion should have a high level of technical expertise and be of sufficient seniority to have the resources and power needed to push through innovation. In a similar study looking at twenty construction project case studies of innovation, Gambatese and Hollowell (2011) came to a different conclusion. They suggested that rather than relying on a champion within the project to push innovation adoption, it was the client or owner's influence which played a stronger role. These two conflicting conclusions add support to the view that innovation champions have an important role to play in the adoption of innovation, but also that that one person cannot necessarily guarantee the outcome.

3.3.6 Managing inter-organisational relationships and the supply chain

The perspective that the process innovation approach brings to the managing of inter-organisational relationships and the supply chain is that as relationships develop within a project team they become a web of interdependent and mutually influential relationships which can be categorised in a framework of characteristics: cooperative, competitive, regulative and conflictual. How this web of relationships emerges, shifts and plays out over the project has been explored in various ways and has a particular importance in construction management literature as the extended supply chain makes these relationships even more complex.

An understanding of the dynamics at work within construction projects was developed through the ideas of loosely and tightly coupled systems within organisations (Weick, 1976) and strong and weak ties between different networks (Granovetter, 1973). These concepts were further developed by Dubois and Gadde (2010) who explored how the complex interrelationships in construction projects enabled or hindered innovation and its adoption.

Their largely conceptual paper distinguished between tight and loosely coupled systems to explain how innovation is accommodated differently in construction projects. Loose couplings between firms in a supply chain allowed for a degree of independence when innovation is introduced, whilst the tighter coupled system of project work made for a high degree of interdependency, and necessitated greater degrees of accommodations when changes were introduced. The idea of tight and loose couplings, and the recognition that innovation adoption affects and is affected by the nature of construction projects, was used by Harty (2010) to develop the idea of relative boundedness to explore the dynamics of adoption. Following the design and introduction of a new ICT system on a large construction project, Harty used ANT (Actor Network Theory) to map the dynamics and the consequences of an innovation, and to account for differences between the initial intention and final outcome of a project. One of the contributions of Harty's research was the recognition that the envisaged outcome of an innovation is often different to the achieved result and that these differences can to some extent be accounted for by the varying degrees of interdependence within the supply chain. In describing construction projects as being relatively unbounded, Harty recognised the complexity of the adoption process in construction projects and called for the collection of more empirical evidence to understand the detail of what occurs during the innovation process.

An alternate view of the supply chain and its effect on innovation adoption has been to attribute project inefficiency and lack of innovative practice to its disparate and fragmented structure (Latham, 1994). Calls have been made to address these inefficiencies by closer supply chain integration and the need to develop closer working relationships between firms (Egan, 1998; Wolstenholme, 2009). The challenges of achieving closer supply chain integration have been highlighted, particularly with regard to issues of collaboration, communication and trust (Bresnen & Marshall, 2000; Briscoe et al., 2001). Briscoe & Dainty (2005) studied the role of small and medium enterprises (SME's) in the supply chain and their perspectives on integration of the supply chain. Using interviews, they pieced together perspectives of different actors within the supply chain and identified barriers to integration. These barriers included issues around lack of trust, quality of information issues, programme related issues and attitude related issues. The reliance of collaborative projects on informal relationships within the supply chain (Bresnen & Marshall, 2000a) and the propensity of principal contractors and clients to form longer-term relationships with each other rather than with subcontractors (Briscoe & Dainty, 2005) are two of the issues signalled as challenges to supply chain integration.

The literature presented so far suggests that the adoption of innovative technologies will present different challenges to different actors within the supply chain, and that issues surrounding integration of the supply chain are likely to be present in the specification of BIPV on buildings. The challenge of adoption of sustainable technologies within the construction sector is often treated as a problem of project team and supply chain integration, with the focus being on professionals and their procedures and competencies (Specialist Engineering Alliance, 2009). While this perspective highlights important issues, the focus on professional roles and formal procedures obscures the complex decision-making processes which explain how and why the solutions are developed and implemented. In addition, it masks adjustments which are made to both the innovation and the building as the process of accommodation proceeds. Little attention is paid to how innovative technologies involving cross-disciplinary issues affect the building in which they are incorporated, or 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.

Although process innovation research looks at the social or managerial implications of the adoption of technology, it does not pay attention to the materiality of the adoption of innovation. In terms of this research process innovation would not account for material developments surrounding the innovation (the building) or to the innovation (the BIPV technology) which occur as the process of adoption plays out.

3.4 The socio-technical nature of the adoption of BIPV in construction projects

This review has led to a clear focus on the phenomenon of the dynamic nature of innovation. The thrust of the discussion has been to explore how this dynamic becomes more complex in the case of the adoption of integrated technologies and within the context of construction projects. This final section therefore focusses on the challenges which might occur during the incorporation of an integrated technology (BIPV) into a construction project and suggests that a socio-technical approach to the study of the adoption process would be appropriate.

The inclusion of an innovative technology which is part of the fabric of a building poses several research challenges. The incorporation of the technology into a construction project necessarily involves extensive accommodation at many levels and in many different ways as it interfaces with many aspects of the project and its components. These accommodations are made both to the technology and to the building in which it fits, and can be in the form of technical adjustments which involve sets of design and solution issues, or of 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 idea of mutual constitution of the technology the building and the project processes challenges previous analytic distinctions between context and innovation.

BIPV offers an example of a technology which is integrated into a building during construction rather than being bolted on after the event. The successful incorporation of BIPV into a building therefore depends on the technology itself, the building within which it is situated and the range of actors involved. This complexity and the preceding review raise three particular challenges. The first challenge is to understand the different requirements which the technology and the building impose on the project team and on each other. The second is to explore the different and sometimes conflicting interests which arise around the implementation of the technology. The final challenge is to follow how the problems and tensions which arise in the course of a project are eventually resolved and how the technology incorporated into the building. These challenges point to the need for fine grained analysis of what occurs when such innovations are introduced and the need for a research approach which allows for consideration of both the technical and social aspects of its adoption.

The combination of technical and social influences is becoming well recognised as having a particularly important contribution to play in understanding the adoption of sustainable innovation within construction projects. Rohracher (2010) recognised the added complexity of sustainable innovation and underlined the contribution that socio-technical studies could make to a deepening understanding of the innovation process in sustainable buildings. What appears to missing from literature is attention to the process of adoption, particularly when incorporating sustainable technology into buildings. This is especially surprising given a growing awareness of the professional and social challenges which sustainable construction poses for the sector (Rohracher, 2001).

Research into projects incorporating sustainable technologies underlines the importance of project team integration (Mollaoglu-Korkmaz et al., 2013), and the need for greater co-ordination of project team members and design features, as well as early involvement of specialist engineers in the design process (Specialist Engineering Alliance, 2009). The introduction of sustainable technologies into buildings can complicate construction by requiring changes in building standard design and building processes. The way that decisions are made, and how the design accommodates the requirements from different actors are important in the understanding the process of innovation diffusion for this technology. Harty's study (2010) drew attention the relative boundedness of construction projects and showed how the original concept of an innovation was translated into a different realisation. Indications that innovations are not fixed, but change and develop as adoption continues, can be found in research by Tryggestad et al. (2010), who used socio-technical studies to show that project goals are not fixed, but develop as the project proceeds. Socio-technical studies have also shown how artefacts themselves can alter the logics of construction (Tryggestad & Georg, 2011), giving weight to the idea of the mutual articulation of the innovation and its local context.

The proposed research began from a simple set of questions concerning the effect of incorporating BIPV on standard building designs and processes. Instead of treating technology as a fixed object, which construction professionals have to accommodate, the premise is that integrated technologies potentially involve the mutual accommodation of both the technology and the building. Any research approach to this research question should focus attention on the succession of problems and solutions which occur as the project proceeds and the resulting design decisions which shape the co-development of both objects.

This analysis, in turn, would provide a basis to track the place of both BIPV and energy issues in the building design from conception to handover.

In summary the process of incorporation of BIPV within a building project will necessitate understanding the interactions between the development of the artefact (in this case the BIPV system within the building), the building into which it fits and the project actors involved in the construction of the building. The following chapter outlines the socio-technical approach which will be mobilized to conduct the research

Chapter 4: Social Construction of Technology

The previous two chapters have drawn attention to the integrated nature of both BIPV and construction projects. Chapter 3 reviewed literature on innovation and its adoption and concluded that building level adoption is a dynamic process which invites further research. An additional outcome from the review of adoption was that adoption of integrated technologies into buildings posed particular challenges and that a socio-technical analysis would allow for a micro-level exploration of the problems and solutions which arise during construction projects.

To explore this research question, the study adopted a Social Construction of Technology (SCOT) approach. For the purposes of this study, SCOT offered three advantages. First, it treated technology as an object in (potentially) continual development and change. Secondly it linked those changes to the network of people and other objects with which it was associated at any given moment in time. Thirdly, it underlined variations in the understandings and expectations which different people brought to decision making as the design was developed. The approach also supported a symmetrical approach to the study of sustainable technology and the building into which they were incorporated. Instead of treating one or the other as fixed, the approach treated both as mutually constituted system(s), supported by socio-technical networks which changed as the technology and the building developed. This allowed the research to follow the mutual influences of process, context and technology as the projects progressed. In contrast to some other approaches for understanding adoption such as Actor Network Theory (ANT), SCOT retains an analytic distinction between the social and the technical and between (fluid) objects (technologies) and the socio-technical networks which support them at any given point in time. It also focuses explicitly on the succession of design decisions which shape the ongoing development of a technology.

The Social Construction of Technology (SCOT) is an approach which is concerned with actors, the way they interact with a new technology and how the new technology is shaped by these interactions. The discussion which follows introduces SCOT as an approach to study the process of adoption and shows how the approach can be applied specifically to the adoption of BIPV. SCOT is usually applied to the development of a single technology and one of the challenges of this research is to apply the approach to the co-development of two complex, integrated assemblages - the technology (BIPV) and the building. SCOT provides a way to understand the interdependencies and interactions between these two integrated assemblages and the project actors as BIPV is incorporated into a building.

4.1 Introduction to SCOT

SCOT is a micro-level socio technical approach which explores the development of technology through a succession of problems and solutions. The approach is used to ask the question: “how can we account for the fact that a technology develops in one way and not in another?” The approach does not assume that the answer is: “it is the way it is because that was the best technical solution”. SCOT sees a technology as the product of negotiations between actors with different understandings and interests.

SCOT is an approach that was developed by Bijker & Pinch in 1984. They used several empirical examples to illustrate their approach, one of which was their study of the development of the bicycle and how it came to be in the form it is today. Their study of the bicycle will be used in this chapter to explain the key concepts of the approach and to illustrate how the SCOT is applied. The approach has been used in a wide range of research topics which include: the development of Bakelite and light bulbs (Bijker, 1999), the re-development of the city of Barcelona (Aibar & Bijker, 1997), the rebuilding of the Tjorn bridge (Walter & Styhre, 2013) and the choice of IT software packages (Howcroft & Light, 2010).

4.2 SCOT: key concepts

This section outlines the five main concepts used in the approach and illustrates how they have been mobilised in research. These concepts are: interpretive flexibility (which accounts for the way that different actors attribute different meanings to the technology); technological frames (which define the different meanings attributed by the actors to the technology); relevant social groups (the groups of actors who adopt the technological frames); problems and solutions (which evolve during the development of the technology); and stabilisation and closure (the mechanism by which the technology becomes at least temporarily fixed). The explanations that follow are derived from Bijker's seminal text book "Of Bicycles, Bakelite and Bulbs" (1999) and are also illustrated by other examples of how the approach has been used.

4.2.1 **Interpretive flexibility**

The SCOT approach uses the concept of interpretive flexibility to draw attention to the multiplicity of meanings that one artefact may have for different groups of people (actors). Using the example of the development of the bicycle, Bijker (1999) identified several different meanings that could be attributed to the bicycle: a means of touring the countryside, a sports vehicle to ride at high speed in competitions, a dangerous device which could break bones, and a vehicle that could allow women to travel freely but which might trap long skirts.

In the case studies which follow, this concept will be used to explore the different requirements that the project actors have of BIPV.

4.2.2 Technological frames

Technological frames are the lenses through which the actors interpret the technology. They are developed from the basic assumptions or elements which produce or support the actors' interpretation of the technology. Elements may include: actors' goals; problem solving strategies adopted; requirements to be met by problem solving; current theories held by the actor; tacit knowledge; testing procedures; design methods; user's practice (Bijker, 1999). The concept of technical frames can be demonstrated using the example of the bicycle and in particular the process of adoption of the pneumatic tyre rather than the solid tyre. One of the technological frames that Bijker identified was that of the Sports Cyclist who required speed and manoeuvrability for racing. In this example, the Sports Cyclist's goal was speed and manoeuvrability, their problem solving strategy was to accept safety risks deriving from higher speed, and their requirements were improvements to speed or manoeuvrability. Current theories held by cyclists who adopted the Sports Cyclist frame included the understanding that faster speed came from solid tyres, which reduced friction. Their tacit knowledge came from the racing characteristics of bicycles that they rode. Testing procedures for the Sports Cyclist were time trials or competitions and their practice was to ride on race tracks or paved areas. In order for the Sports Cyclist to adopt the new-fangled pneumatic tyre, they had to be convinced that the new tyre would satisfy their desire for faster speeds. Other users with a different technological frame were concerned with reducing vibration from the solid tyres, but this aspect of the pneumatic tyre would not have been important to the cyclists who adopted the sports cyclist frame.

The elements of a technological frame are not fixed but are modified by the researcher to reflect the research topic and aims of the project. One example of this variation was shown by Prell (2009), who used SCOT to study the development of an information system called “Connected Kids”. She included Bijker’s original elements of goals, problems, strategies, tacit knowledge and exemplary artefacts, but added the element of key material resources which was relevant to her study of the information system. In the case studies which follow, this flexibility will be applied to reflect the actors’ interpretations of the technology.

4.2.3 **Relevant Social Groups**

If a technological frame is the lens through which actors interpret the technology, then a Relevant Social Group (RSG) is the group of actors who share the same frame. In the case of the bicycle, Bijker and Pinch (2012) identified five groups of users who had different requirements of the technology: Elderly Men, Tourist Cyclists, Women Cyclists, Sport Cyclists and Producers. As this suggests, RSGs are not groups of actors who share the same job title (architects, lawyers, doctors), but are actors with similar expectations of a particular technology. This distinction allows the analysis to move beyond formal categorisations, and allows a nuanced understanding of how alliances between actors emerge around the technology. For example, in a study of the development of the layout of the city of Barcelona in 1854, Aibar and Bijker (1997) initially identified relevant social groups which were aligned with job descriptions - these included engineers, architects, working class people, property owners and the government. By the end of the research the authors concluded that as the plans for development progressed, different alliances were formed which no longer corresponded to occupational groupings. In the case studies which follow, the concept of RSGs will allow an analysis of the shifting alliances and rationales for decision-making.

4.2.4 Problems and Solutions

The fourth concept taken from SCOT is that of problems and solutions. In a SCOT analysis the development of the technology is analysed in terms of the problems and solutions that arise as the technology is developed. Each RSG defines problems in a certain way and brings with them solutions that fit with their interests. At any given moment there are RSGs which have problems with the technology for which they want a solution. Decisions are taken as a result of the conflicts and the resulting negotiations between RSGs, and an analysis of the succession of problems and solutions is used to explain the development of the technology. Negotiations, conflicts and choices are analysed to identify networks of different groups, problems and solutions to show important moments in the decision-making process as the technology develops.

The evolution of the bicycle frame can be used to illustrate this process of unfolding development. One of the most popular designs of bicycle had one large wheel at the front and a smaller one at the back. This was primarily to allow for direct drive of the front wheel by the pedals or levers on the front wheel. The elevated saddle position made it hard for ladies with long skirts to mount and made falling off dangerous for all riders. Tricycles were designed to be easier for ladies with restricting clothing to ride, but became dangerous as the three tracks (one from each wheel) made it hard to avoid stones and holes in the road. The development of the gear train made it possible to develop a trapezoidal frame with the pedals in the centre of the bike and two similar sized wheels. Thus, the problems of different user groups were played out as the designs developed and the solutions chosen explained the development process (Bijker, 1999). In the case studies which follow, the approach is used to identify the problems and solutions which occur, and then to explore the network which ‘explains’ the development of different solutions and the eventual decisions taken.

4.2.5 Stabilisation and closure

The concept of Stabilisation and Closure relates to the way in which the features of an artefact are negotiated and become stable (Humphreys, 2005). Stabilisation and closure have been described as being “two sides of the same coin” and “two aspects of the same process” (Bijker, 1999. p85). Stabilisation is used to describe the process by which the design of artefacts becomes more fixed, whilst closure refers to the mechanism by which the interpretive flexibility between groups decreases through negotiation and conflict. Two mechanisms of closure are theorised: Rhetorical Closure (where the groups see the problem as being solved) and Redefinition of the Problem (when a new way of defining the problem eliminates the original problem) (Bijker, 1999). In the example of the bicycle, Rhetorical Closure occurred when the gear train and design of the frame brought about a lower riding position and solved the problem of rider safety. Redefinition of the Problem can be illustrated by consideration of the way the pneumatic tyre became accepted. The new tyre was introduced as an anti-vibration solution, but was opposed by the sports cyclists who saw the tyres as a liability because of the risk of punctures. The air tyre was universally adopted only after the sports cyclists realised that the new tyres also gave increased speed and so they no longer worried about the danger of punctures. In the case studies which follow, the concepts of stabilisation and closure will be used to look beyond the simple mapping of problems and solutions, and will explore how decisions were taken and why certain pathways were followed.

SCOT is not without critics and Bijker and Pinch have developed the approach further in response to these. Early criticisms included concerns about the lack of consideration of the effect of historical and social influence on actors (Russell, 1986; Winner, 1993), the lack of appreciation of the effect of power asymmetry between groups (Klein & Kleinman, 2002) and the subjective way in which groups were defined (Clayton, 2002). In answer to some of these criticisms, Bijker and Pinch developed the concept of technological frames which was used to characterise actors according to their goals, key problems, problem solving strategies etc. (Bijker et al., 2012).

The subjective nature of the SCOT has also been criticised in terms of the choice of sources used by the researcher, the subjective assignment of groups and the simplistic nature of the method (Clayton, 2002; Epperson, 2002). In response Bijker (2009) acknowledged the subjectivity of the method but stressed that the focus of the approach was not on the technology per se, but rather on its development. Although less good at identifying broader structural characteristics (Klein & Kleinman, 2002), the approach does allow the study of specific decision-making processes and contingent events which affect the development of technology. In terms of the study of the adoption of BIPV, although the approach may obscure issues of project organisation or management style (which may indirectly have influenced particular decisions), the analysis does give a very clear idea of how and why solutions were adopted and how the process of adoption unfolded within a case study.

This section has outlined the main concepts of the SCOT approach and illustrated their use with empirical examples. What follows is a discussion of how the concepts can be used to apply SCOT to the analysis of a case study.

4.3 Applying SCOT

This section uses Bijker’s approach as laid out in “Of Bicycles, Bakelite and Bulbs” (Bijker, 1999) to illustrate how the SCOT approach has been mobilised in the study of the adoption of technology in a construction project. The discussion introduces SCOT diagrams as a way of mapping the development of an artefact as a succession of unfolding problems and solutions.

Bijker's original example of the development of the bicycle is used to illustrate the approach. Section 4.4 draws on this discussion to explore the application of SCOT to BIPV. Chapter 5 provides a detailed explanation of how the SCOT approach was used in this dissertation.

In a SCOT approach, analysis starts with the choice of a technology, breaking it down into its various component parts (the technological assemblage of the bicycle is broken down into parts such as tyre, frame, brake mechanism, saddle etc.). The researcher then selects one of those components as a starting point and uses the component to identify actors who were involved in its development. Actors who have common interests in the artefacts are identified and their interests are summarised in terms of technological frames and relevant social groups. As discussed above, in the case of the bicycle, interests included concerns over the performance of the bicycle (speed and manoeuvrability), the safety of the bicycle, etc. Once the RSGs have been defined, the analysis proceeds by exploring the successive definition of problems and development of solutions for each artefact, until a picture of the development of the whole technological assemblage is established.

Central to the approach is the production of SCOT diagrams - the visual representation of the network of artefacts, actors, problems and solutions that occurred during the development of the technology. This network of technological development is drawn up with the artefacts at the centre of the analysis. RSGs are identified through their shared technological frames and ranged around the artefacts.

Figure 4-1 illustrates how this network is represented.

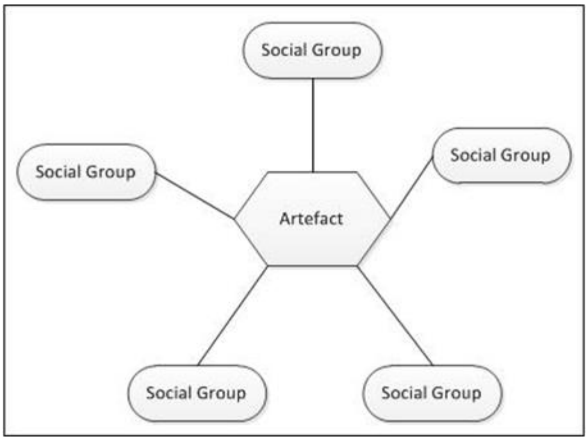


Figure 4-1: The relationship between an artefact and the relevant social groups (Bijker et al., 2012; p29)

In a similar way, the problems represented by each artefact to each relevant social group are then identified and added to the diagram. Figure 4-2 illustrates how this network is represented

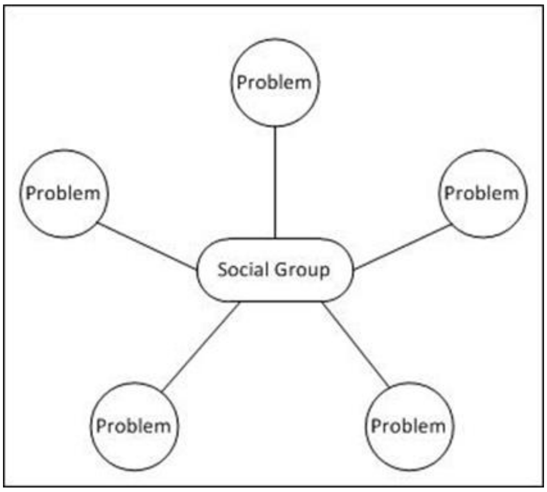


Figure 4-2: The relationship between one social group and the perceived problem (Bijker et al., 2012; p29)

Finally the solutions - both proposed and adopted, are added to the diagram and the network unfolds, showing the configuration which forms around each problem, and the possible proposed solutions, as the assemblage is incorporated into the building. The development of these diagrams is seen as an essential part of the analysis path of decisions (Bijker et al., 2012).

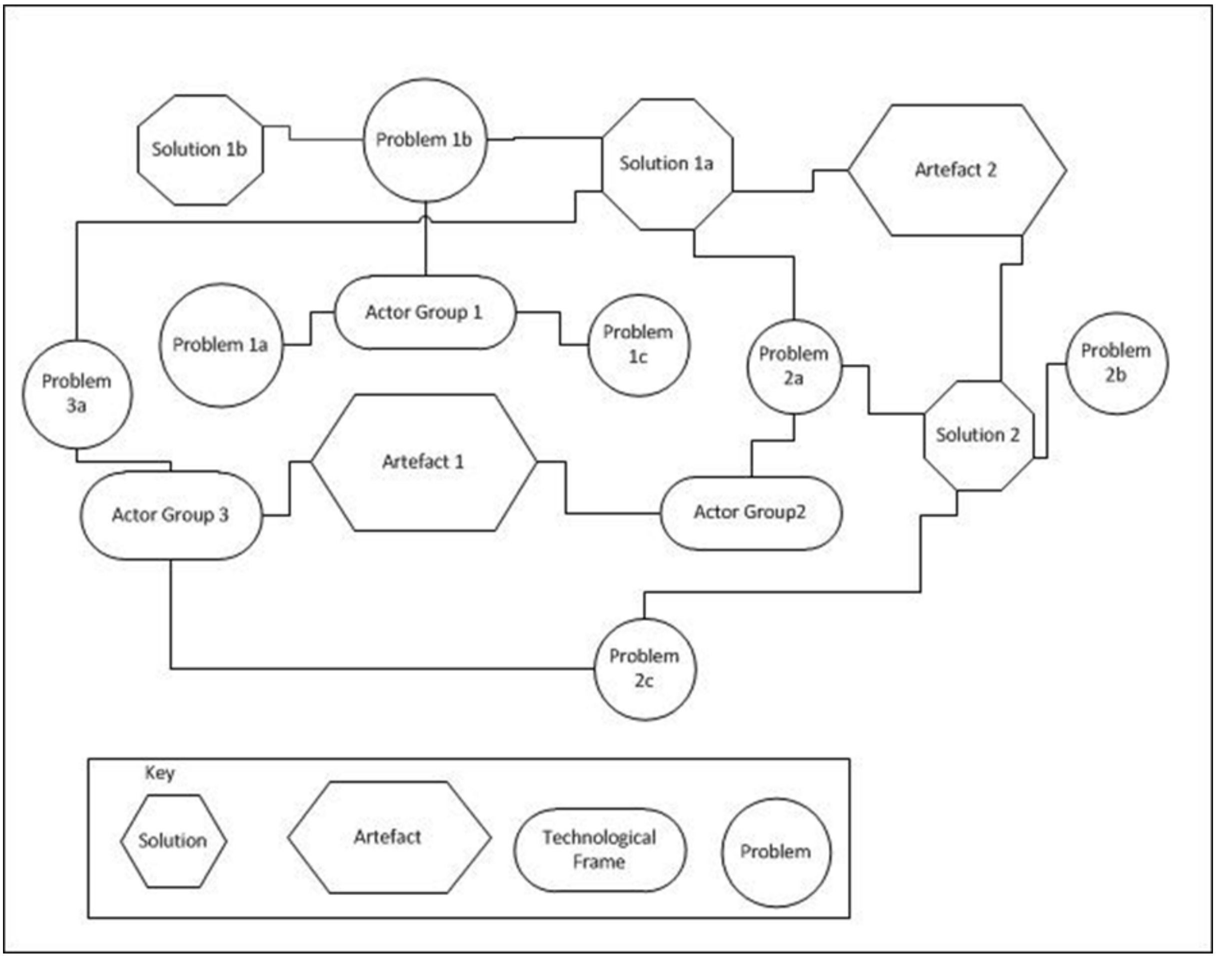


Figure 4-3: Schematic representation of SCOT analysis

As Figure 4-3 indicates, in Bijker’s method (Bijker et al. 2012), the heterogeneous assemblage is depicted as a network of components or artefacts (hexagons) and actor groups who have particular involvements with these artefacts are added (lozenges). Problems with the artefact which the RSGs identify are mapped to the artefact (circles) and possible solutions are added (octagons). One particular benefit of these diagrams is that they highlight the way in which a solution which resolves a problem for one RSG creates a different problem for another. In this way the process of problem solution and technological development can be followed.

4.4 Mobilising SCOT in the study of BIPV

This section outlines how the SCOT approach has been mobilised to study the incorporation of BIPV into a building. Chapter 5 goes on to give a full account of the research methods.

This study uses the SCOT approach to explore the adoption of BIPV. In contrast to many commercial technologies that achieve a certain degree of stabilization prior being commercialized, BIPV in the UK is largely a bespoke technology, which is integrated into the façade or roof of the building. As such, it has complex interdependencies with building design. The successful incorporation of BIPV into a building (which itself comprises many elements and assemblages) depends on the technology itself, the building in which it is situated and the range of actors involved. As a lens through which to view the adoption of a technology, SCOT highlights the technical issues raised by the introduction of BIPV, the relevance of those issues to the project actors, the solutions which were proposed and selected, and the impact of these on BIPV and the build process. In turn this analysis allows for the consideration of key moments in the development of BIPV, the reasons behind these choices and, importantly, the knock-on effects to the building design and construction process.

In the same way that the bicycle was analysed as an assemblage of parts, the building comprises many sub-systems which could also be considered in this way. For example the heating, ventilation and air conditioning (HVAC) system, lighting system and electrical system all interface with each other to form the building. Using Bijker’s bicycle analogy (Bijker, 1999), the BIPV system is similar to a gear train assembly which is an integrated technology incorporated into the bicycle (in this case the building). For clarity, this SCOT analysis is restricted to the BIPV artefacts and the elements of the building with which they directly interface. The parts of the building directly affected by BIPV include artefacts such as the building façade and building electrical system. Each of the BIPV components has characteristics which are interpreted differently by different groups and which are considered to be part of the building itself. For example, the BIPV panel assembly forms part of the waterproof façade and is also an important part of the aesthetic quality of the building.

SCOT diagrams are used to map out the sometimes conflicting requirements which different groups have of BIPV and the building (for example, the architect may want a smooth appearance, whilst the design engineer might need an angled façade). The mapping also includes the issues which arise in the incorporation of the technology, and the various solutions which are proposed to solve each problem. This exploration of the succession of problems and solutions shows how BIPV is included or absorbed into the building. The processes of stabilisation and closure are used to consider how the BIPV system and its interfaces with the building developed. In this research, rather than the more usual study of the negotiations which lead to the stabilization of a generic version of the technology, it is the co-development of the building and BIPV system which is studied.

There are several key concepts to carry forward from this review. Firstly that RSGs are composed of project actors who share a view of the technology, rather than those who occupy common positions or roles. Second, that project actors do not necessarily remain in one RSG throughout the project, and might be part of more than one RSG at one time. Third, that solutions to problems develop from the negotiations between RSGs as the project develops. Finally that the mechanisms of closure and the process of stabilisation relate to the co-development of the BIPV system and the building, rather than the stabilisation of generic BIPV systems. As this brief discussion suggests, a particular strength of using SCOT to study the incorporation of BIPV into a building is that it can be used to understand interdependent technical developments in a complex environment, by paying attention both to the actors involved and to the context in which it is developing. The following chapter details the methods used in this research.

Chapter 5: Methods

This research explores the dynamic nature of the process of adoption. The general research question being asked is: “what accommodations are made both to the innovation and to its local physical and processual context during the adoption of an innovation?” This research operationalises the general research question by studying the micro-level occurrences which unfold when an innovative technology (in this case BIPV) is specified on a commercial building project. The specific research question asks “how does the mutual articulation of a building and the technology develop as BIPV is incorporated within a building?” The preceding chapter outlined the SCOT approach, its ontological model and the fit of the approach to the research object and question. This chapter details the research design, outlines the methods used to conduct the research, observes the limitations to the approach and outlines the ethical considerations of the research.

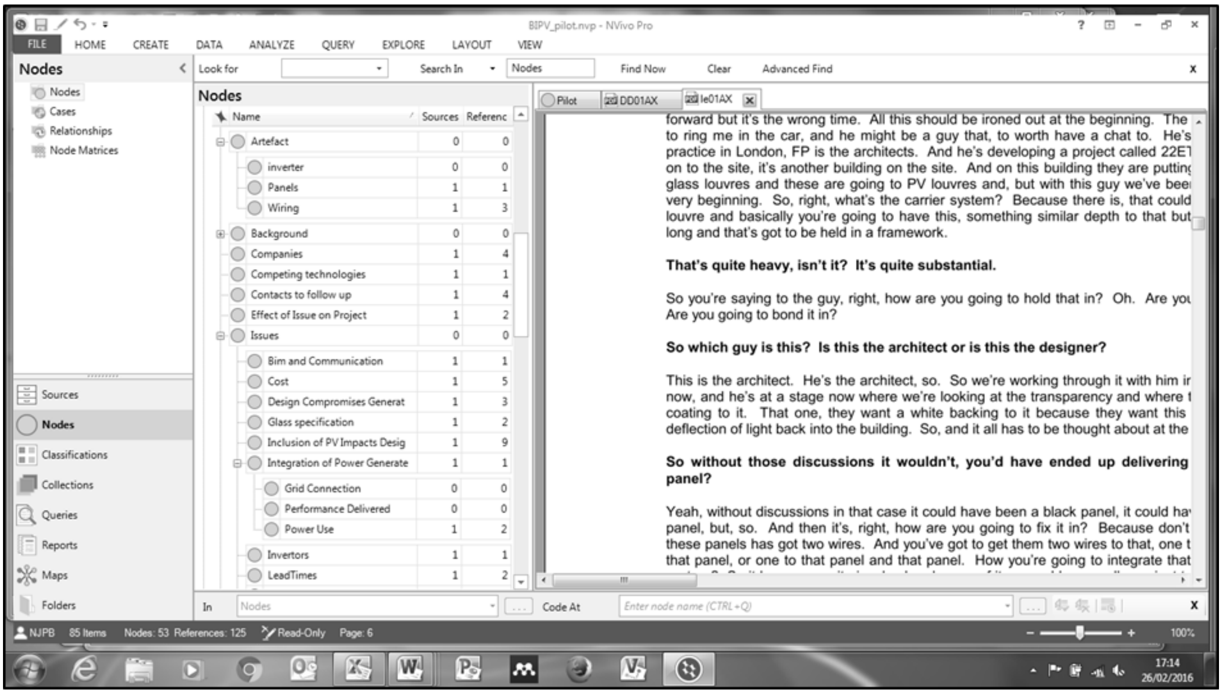
5.1 Research design

This research was conducted in three parts. First a pilot study was carried out to gain a deeper understanding of the issues involved and to inform the main research. Secondly, the research followed three projects and used a Social Construction of Technology (SCOT) approach to explore the adoption of BIPV in each case. Finally a cross case analysis was used to further analyse the three case studies to explore the dynamics of adoption of BIPV.

5.2 Pilot Study

The pilot study was carried out to produce an initial mapping of the challenges which occur in construction projects as BIPV is incorporated and to confirm that SCOT was an approach capable of handling the complexity of the mutual constitution of BIPV and a complex building. The aims of the pilot study were: to gain a deeper understanding of the challenges of incorporating BIPV in construction projects; to develop and refine the application of SCOT; to refine interview questions; and to develop coding nodes for NVivo analysis and methods for drawing SCOT diagrams. The use of pilot studies to refine research design is supported by Bryman (2008) and Bazeley (2013) as a "dry run…to determine whether your data will generate analysable data that are relevant to your purpose" (Bazeley, 2013. p55).

The framework of the pilot study was to conduct interviews with three people who much of experience of the practicalities of BIPV in construction projects. It used interviews to identify some of the challenges that they had experienced in the incorporation of BIPV on a project and then analysed these interviews using a SCOT framework. Semi-structured interviews were used because of their flexibility, which allowed exploration of the way in which the interviewee framed and understood the events and issues around the adoption of BIPV. A sample interview schedule is given in Appendix A1. The interviews lasted for approximately forty five minutes and each was recorded. Afterwards each interview was transcribed, anonymised and then coded using NVivo 10 software. The nodes were established using a provisional coding strategy which provided a "start list set of codes prior to fieldwork" (Miles & Huberman, 1994, p58). These nodes were developed from the SCOT framework and focussed on actors and their interests, artefacts, issues, problems and solutions (Bijker et al, 2012). In addition to these nodes, other nodes were used to code for professional background, motivations for using BIPV on projects, previous involvement with BIPV, project descriptions, project procurement methods, project stages in which they were involved and potential case studies and contacts to follow up. These additional codes were derived from the literature which indicated that all of these issues may be important in understanding the context of the adoption. For example, procurement methods have been shown to affect problem solving and attitudes to risk (Gruneberg et al., 2007) and innovation over the development of a project has been shown to vary (Harty & Whyte, 2010). Figure 5-1 below shows a screen shot of the pilot project and the codes used.



Nodes

Name	Sources	Referenc
Artefact	0	0
inverter	0	0
Panels	1	1
Wiring	1	3
Background	0	0
Companies	1	4
Competing technologies	1	1
Contacts to follow up	1	4
Effect of Issue on Project	1	2
Issues	0	0
Bim and Communication	1	1
Cost	1	5
Design Compromises Generat	1	3
Glass specification	1	2
Inclusion of PV Impacts Desig	1	9
Integration of Power Generate	1	1
Grid Connection	0	0
Performance Delivered	0	0
Power Use	1	2
Invertors	1	1
LeadTimes	1	2

forward but it's the wrong time. All this should be ironed out at the beginning. The
to ring me in the car, and he might be a guy that, to worth have a chat to. He's
practice in London, FP is the architects. And he's developing a project called 22E
on to the site, it's another building on the site. And on this building they are puttin
glass louvres and these are going to PV louvres and, but with this guy we've bee
very beginning. So, right, what's the carrier system? Because there is, that could
louvre and basically you're going to have this, something similar depth to that but
long and that's got to be held in a framework.

That's quite heavy, isn't it? It's quite substantial.

So you're saying to the guy, right, how are you going to hold that in? Oh. Are yo
Are you going to bond it in?

So which guy is this? Is this the architect or is this the designer?

This is the architect. He's the architect, so. So we're working through it with him i
now, and he's at a stage now where we're looking at the transparency and where
coating to it. That one, they want a white backing to it because they want this
deflection of light back into the building. So, and it all has to be thought about at the

**So without those discussions it wouldn't, you'd have ended up delivering
panel?**

Yeah, without discussions in that case it could have been a black panel, it could ha
panel, but, so. And then it's, right, how are you going to fix it in? Because don't
these panels has got two wires. And you've got to get them two wires to that, one
that panel, or one to that panel and that panel. How you're going to integrate that

Figure 5-1: NVivo screen shot for pilot study

The three interviewees were selected for their very different perspectives and experiences of the inclusion of BIPV in projects. The first was a BIPV laminate supplier, the second a consultant and BIPV governmental advisor and the third a project manager in charge of the sustainable development programme of a large UK retail company. Their long-term involvement with BIPV allowed them to comment on over 30 projects and gave insights into the accommodations made on projects in which BIPV is specified.

Table 5-1 summarises the characteristics of the interviewees in terms of their historical involvement with BIPV and the role that they currently filled.

	Interviewee 1	**Interviewee 2**	**Interviewee 3**
Years associated with BIPV	15	30	10
Roles undertaken	Façade Engineer Façade Sales Manager BIPV Sales Manager	M&E Engineer Head of PV Business Development BIPV consultant BIPV Advisor to government	Head of Sustainability Initiatives Manger Engagement and project Manager
No of projects identified during interview	10	15	5-10 discrete projects 100+ related projects
Involvement with BIPV research and development	Yes	Yes	Yes
Current main project role	Supplier	Consultant	Project Manager

Table 5-1: Characterisation of pilot study interviewees

The coding from these interviews was used to characterise the technological frames (the cognitive, social and technical elements that guide or constrain meanings and behaviours relevant to an artefact (Prell, 2009) which were mobilised by project actors in the context of BIPV. As indicated in Chapter 4, the determinants of a technological frame are: the actors' goals; the types of problems they see; the types of solutions they offer; the strategies they tend to use in solving problems; the theories that they use; the tacit knowledge that they have; the testing procedures; design methods; and criteria that they use (Bijker et al., 2012).

Each interview covered project experiences of the interviewee over many projects (32 projects were discussed over the course of the three interviews). Data were analysed to identify different ways in which the technology had been interpreted by different individuals on the projects discussed. These different interpretations or understandings were explored in terms of the goals of the individual when they considered the technology, problems commonly experienced by the individual, strategies used to uphold the interest of the group, the knowledge that the individual uses to maintain the goal, what criteria the individual used to test the success of the goal, and how this was carried out and measured.

As the interviews were analysed, common patterns of interests were seen across the 32 projects and these were recorded on an outline table distilled from the SCOT approach outlined by Bijker et al. (2012). Table 5-1 gives an example of how an individual's interpretation of the technology was developed.

	Interpretation 1
Goals	- Buildings should generate energy - Reduction of carbon emissions
Problems	- Green solutions are often "casualties of war" - Green solutions generally cost more
Strategies	- Enshrine in planning regs
Tacit Knowledge	- Technology available - Planning requirements
Testing procedures	- Output figures - m2 of PV
Design methods	- BREEAM
Criteria	- Merton, KWh

Table 5-2: Sample grid of individual interpretation of technology

As the analysis developed six common technological frames were identified from the data and these are outlined in Table 5-3 below and detailed in Appendix A.3. These technological frames were named as; Green Guardian, Cost Watcher, Generation Maximiser, Design Aesthete, Design Optimiser and User.

The six technological frames each had distinctive criteria, concerns and interests. Design Aesthetes were concerned with the look and feel of the building, seeing BIPV as being an integral part of the building identity and making a positive contribution to the design aesthetics. Green Guardians were mainly concerned with carbon emission reductions and renewable energy generation. Their concern was motivated mainly by the desire to meet planning or BREEAM requirements. Design Optimisers were less concerned about the individual aspects of the project, but rather with ensuring that the design process was efficient and that details were clarified before construction started. Generation Maximisers were concerned with ensuring that the BIPV assemblage generated as much electricity as possible - both in terms of fulfilling the planning conditions and of contributing to reduced running costs. Users were the actors concerned with the final product - they required the PV system to supply electricity in a way which had no negative impact on the day-to-day running of the building. These frames, together with their main interest are summarised in Table 5-3

Technological Frame	**Main interest of Technological Frame**
Design Aesthetes	BIPV is part of the building which is a flagship architectural design
Green Guardians	BIPV reduces carbon emissions of the building and meets planning requirements
Design Optimisers	The process of design is efficient
Generation Maximisers	The PV system generates to its maximum potential
Cost Watchers	Project costs are kept to a minimum and financial case is maintained
Users	The system is fit for purpose and the generation does not negatively impact facilities management.

Table 5-3: Technological Frames and their interest

The second task of the pilot study was the definition of the artefacts to be considered in the adoption of BIPV. Prior to the pilot study, four artefacts had been identified: the building; the

BIPV panels; the BIPV wiring; and the inverters. During analysis these were augmented by a finer division: the part of the building to which the BIPV system was attached (e.g. roof, façade, etc.); wiring (before the inverter); cabling (after the inverter); the G59 cabinet and meter; the PV cells; and the laminated glass PV panels.

Once the technological frames and artefacts had been defined, coding was used to identify problems and solutions for the adoption of BIPV. These four elements (artefacts, technological frames, problems and solutions) were then used to develop SCOT diagrams in line with the outline presented in Chapter 4. Starting with the artefact, the technological frames concerned were added, followed by the problems that were experienced by the actors within the technological frames. The solutions to the problems were then added and the unfolding network of artefacts, technological frames, problems and solutions was developed.

One vignette from one of the interviews illustrates how the diagrams were developed and illustrates how the co-development of the BIPV system and the building occurred. BIPV was included on the roof of a new football stadium. Rather than being a roof-mounted system, the photovoltaic panels were integrated into the roof structure and the resulting opacity used to provide solar shading for the spectators. The BIPV was designed to meet renewable generating requirements from the local authority, to use the opacity of the roof-integrated PV panels to provide shading to spectators, and to enhance the aesthetic appeal of the building. In this extract Interviewee 1 explains that this shading affected grass growth on the pitch and that, as a result, the spacing of the PV cells had to be adjusted to allow for even grass growth.

> Football stadia roofs are ideal - you put PV in, and it’s giving a nice bit of shading and it’s giving light, but [at] certain times of the year it’s also shading the grass, so the grass won’t grow evenly, so they’ve had to alter the spacing of the panels to make sure that there is the same level of light [on the grass].
>
> Pilot study Interviewee 1

The interviewee went on to talk about the re-work that this required and the subsequent reduction in generation potential. The artefact under consideration in this case was the panel assembly which included the façade configuration and generating characteristic. The RSGs in this instance included Design Aesthetes (who were concerned with creating an interesting and pleasing roof construction as well as using green technology to generate electricity), Cost Watchers (who were concerned with minimising project costs and optimising generation potential) and Users (who were mostly concerned with the maintenance of the stadium and care of the grass). The problems and solutions which were identified between RSGs and their effect on the parts of the assemblage are illustrated in Figure 5-2 below.

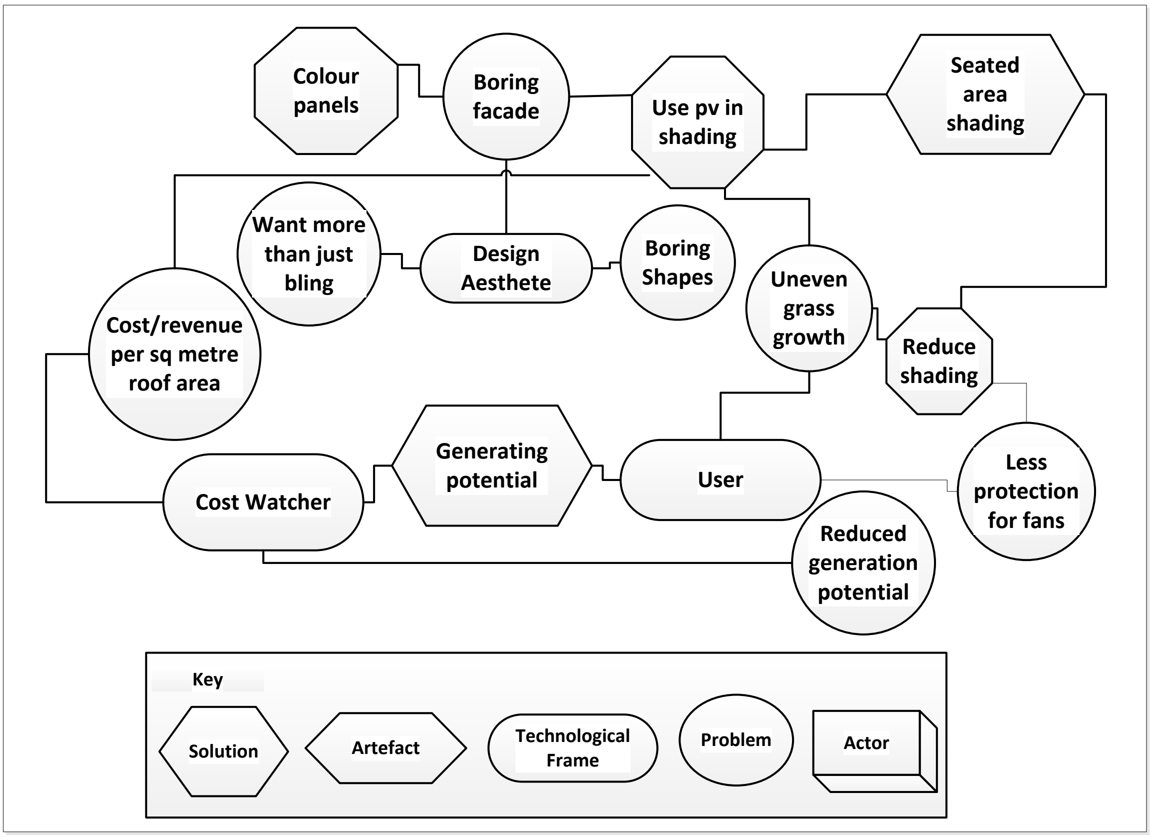


Figure 5-2: SCOT diagram for unanticipated shading

As Figure 5-2 illustrates, the use of BIPV to provide shading as part of the façade configuration addressed the Design Aesthetes concerns and was supported by the Cost

Watchers. The User group was unaware of the impact of the solution on grass growth, but when the stadium was brought into use, this became a major problem. Shading was in tension both with the visual impact of the building (part of the aesthetic appeal of the panels) and the generation potential of the façade configuration. Faced with this problem, it was decided to reduce the shading density of the roof by reducing the density of photovoltaic (PV) cells in the roof. This decreased the generation potential of the stadium and so affected project payback - a direct concern of both Cost Watcher and User RSGs. The solution also impacted the Design Aesthetes by changing the homogeneity of the design, decreasing the opacity and therefore the shading of spectators. The solution was a result of the negotiations during which the User group's need for a playable pitch was recognised by the other groups.

The aim of the pilot study was to practice using the SCOT approach, to refine interview questions and to develop coding nodes for NVivo analysis and methods for drawing SCOT diagrams. Appendix A.2 shows the development of the interview schedules - questions added included more contextual information, references to other actors involved and their roles in the solution or the raising of problems, knock-on effects of solutions and the particular stage at which problems occurred. Nodes for coding were expanded to include: specific mention of interfaces with parts of the building; other firms or parts of the PV system; details about contracts used on the project; design evolution. More nodes were also added to allow for the definition of technological frames (goals, meaning the actor ascribed to the technology, and tools used when dealing with the technology). Figure 5-3 shows some of the changes made to the coding for the case studies. The development of SCOT diagrams was not straightforward and it became clear that not only did every element of the BIPV system and the parts of the building which were impacted by the BIPV need to be included as artefacts, but that some artefacts that were not present in material form, such as contracts and the project schedule, needed to be considered as well.

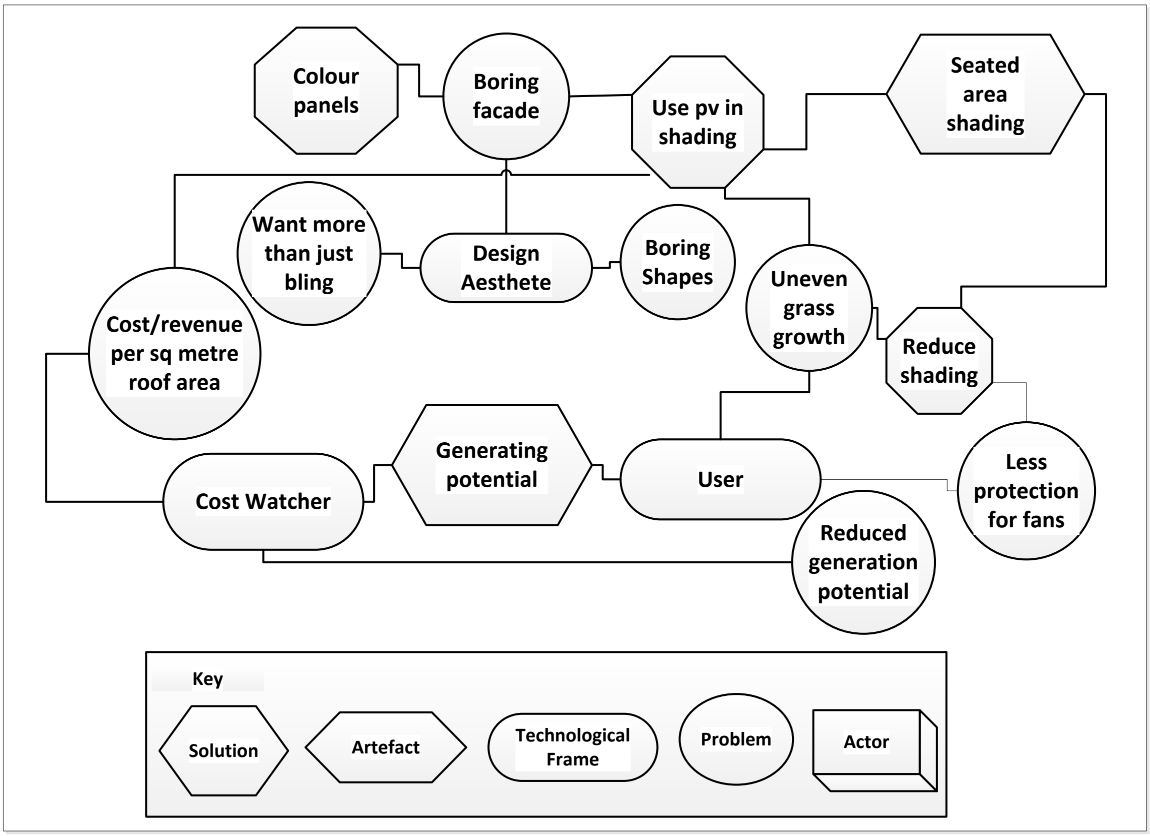


Figure 5-3: NVivo coding for case study

The pilot study achieved its aims and further informed the main research by augmenting the definition of artefacts, developing and refining the concept of technological frames to be used in subsequent analysis and establishing the concept of co-development of the BIPV system and the building.

5.3 Case Studies

SCOT requires detailed analysis of the particular circumstances and developments around a defined technology. Case study entails “the detailed and intensive analysis of a single case” (Bryman, 2008. p54) and focusses on the complexity and particular details of that case in its own right. For these reasons a case study approach was appropriate for this research. A cross case analysis element was added to the research design to get a sense of type of variations and mechanisms which occurred during the adoption process.

The research is concerned with commercial, new build projects which incorporate BIPV. Given the transient nature of project teams, the projects had to be recent so that the actors could be tracked down and interviewed. In addition the BIPV technology used had to have similar characteristics in terms of the type of PV cell and substrate, so that a comparison could be made without the complication of a different set of technical problems arising from different technologies being used. Finally the projects had to include some different applications of BIPV so that similarities and differences in the problems in the adoption of BIPV could be explored. Having established the criteria for the selection of case studies and conforming to the SCOT approach of following the technology (Bijker et al., 2012), three manufacturers of BIPV laminate panels were approached and invited to participate in the research. One of the manufacturers agreed to be interviewed for the pilot study and during the interview was asked to identify projects which met the criteria described above. The manufacturer identified five possible cases which all used his PV laminate panels and passed on the details of five contacts - one for each project. When contacted, three of the five contacts agreed to seek permission from their client to be part of the research, on the understanding that all data would be anonymised. Permission was given in all three cases and these became the three case studies followed in this research.

5.3.1 Case study overview

Vogue Terrace is a commercial office building in Central London which was part of a three-phase refurbishment project in which three adjacent blocks were reduced to a skeleton and then reconstructed. Although not exactly a new-build, the refurbishment was so extensive that it fulfilled the criteria of case selection. BIPV technology was incorporated in the brise-soleil louvres on the south elevation of the building. The development started in the mid-2000s, with Vogue Terrace being the last of the three buildings to be constructed. Initial planning permission for Vogue Terrace was granted in 2007, work on site began in August 2014, with work on the BIPV installation commencing in February 2015. The project used a “Design and Build” contract

Future Green is a commercial science hub set on a 24-acre site in a large science park development in Northern England. The BIPV system was incorporated into the windows of the south elevation of the building. Design for the project started in 2010, construction began in late 2013, the installation of BIPV was completed by August 2014 and the Future Green project was completed by November 2014. The project used a Design and Build contract and was a joint partnership between a university, the City Council and several other partners.

Synergy Court is an interdisciplinary biomedical research centre in Central London which was designed to serve a medical research partnership between three national research organisations and three universities. The BIPV system was incorporated into roof fins on the building. Project planning began in 2001, with planning permission being granted in December 2010. Ground works began in April 2011 and BIPV installation began in 2014, the estimated completion date being early 2016. The project used a Design and Build contract.

Table 5-4 presents a summary of the three case studies in terms of their use, type of BIPV application and timeline of construction.

	Vogue Terrace	**Future Green**	**Vogue Terrace**
Use	Commercial Offices	Science Hub	Medical Research Centre
BIPV system	Brise-soleil louvres	Windows	Roof fins
Planning permission	2007	2009	2010
Construction start	2014	2013	2011
Completion date	2016 (estimated)	2014	2016 (estimated)
Contract	Design and Build	Design and Build	Design and Build

Table 5-4: Summary of case studies

5.3.2 Sampling

The selection of interviewees and the boundaries of the sampling for each case study were set by the technique of "snow-balling" (Bryman, 2008), where initial contact was made with one project actor and this contact was then used to establish contacts with others. Whenever no new contacts were identified by the project actors the case was considered complete. This process of snow-balling and following the actors is advocated by Bijker (1999).

The frame for sampling (Miles et al., 2014) was set by the SCOT approach, which calls for the research to follow the actors and to explore the issues that are identified by them. In this way, the technology was thought of as an assemblage of components or artefacts, and the interviews followed these artefacts through the eyes of the actors, noting where the artefact was changed or where the interaction with another artefact brought about additional challenges.

5.3.3 Interviews

Case study interviews followed the method outlined in the pilot study, in which semi-structured interviews were demonstrated to provide adequate depth and to reveal rich data about the incorporation of BIPV into buildings. The structure allowed the exploration of problems and solutions, with interviewees being encouraged to elaborate on each issue. Interview schedules were modified before each interview, to take into account any issues that had been raised in previous interviews. This ensured that each actor could comment on the same issue and contribute their view of the situation. Appendix A2 presents an example of an interview schedule used in case study interviews.

A total of twenty eight interviews were conducted in addition to the three pilot interviews. Two e-mail correspondences were also entered into, to discuss particular aspects of the projects with project actors who were unwilling to be interviewed. A comparable set of project actors from each case study was interviewed. Most actors were only interviewed once, with the exception of the PV laminate supplier who was interviewed for both the pilot study and for the case studies, and the architect for Vogue Terrace who was interviewed four times as the design of the project progressed. Table 5-5 details the actors interviewed and the dates of each interview. The laminate supplier was common to all three case studies and was the only interviewee to cover all three case studies.

All of the interviewees were assigned a unique identity (ID) number and transcripts of the interviews were anonymised and given the corresponding ID number. Transcripts were checked to ensure that all projects, places, firms and actors referred to were anonymised. A key of anonymised words was kept for all interviews. All interviewees were thanked for their participation and - when requested - transcripts were offered to the interviewees for checking to ensure that they were happy with the interview content being included in the research. All interviewees agreed that their interview could be included.

Vogue Terrace		**Future Green**		**Synergy Court**	
Position	**Date**	**Position**	Date	**Position**	**Date**
Laminate Supplier: Sales Manager	10/02/2013 16/04/2015	Laminate Supplier Sales Manager	10/02/2013 16/04/2015	Laminate Supplier: Sales Manager	10/02/2013 16/04/2015
Architect	26/03/2014	Architect	19/08/2014	Architect	11/04/2014
	18/07/2014	Mechanical Design Consultant	19/08/2014	Louvre Supplier Sales Manager	14/03/2014
	15/10/2014	Electrical Design Consultant	19/11/2014	Louvre Supplier Managing Director	03/06/2015
	07/01/2015	Façade Design Director	28/11/2014	Louvre Supplier Design Director	03/06/2015
Façade Sales Manager	11/02/2015	Glazing Supplier Project Manager	27/11/2014	Louvre Supplier Project Manager	14/06/2014
Façade Project Manager	08/07/2015	Main Contractor Design Manager	05/07/2014	M&E Consultant Associate Director	11/06/2014
Façade Consultant	23/06/2015	Main Contractor M&E Services Manager	05/07/2014	M&E Consultant Electrical Engineer	11/06/2014
Main Contractor Design Manager	25/02/2015	M&E contractor Project Manager	19/11/2014	Main Contractor Package Manager	14/10/2014
Main Contractor M&E Manager	25/02/2015	Site Electrical Contractor	19/11/2014	Electrical Contractor Lead Engineer	14/10/2014
Wiring contractor Project Manager	13/05/2015	Client Project Manager	19/08/2014	Client	13/10/2014
		Lettings Manager	19/11/2014	Planning Officer	16/10/2014

Table 5-5: Table of interviewees

5.3.4 Documents

Interviewees were asked to bring supporting documents to their interviews and in most cases they did. These documents were in the form of drawings, photographs and specifications. In one case the interviewee brought his laptop and illustrated his points with the BIM model of the façade installation. In another case an architect brought a power point presentation to illustrate the evolution of the building and BIPV system. All of the documents that were given to the researcher were archived, after being assigned document numbers which corresponded to the interviewee ID number. Photographs of each project were taken to show the context of the BIPV, the building into which it is incorporated and details of the PV installation. Publically available documents in the form of PR reports and Company press communications were consulted to give context to the case studies.

5.3.5 Design and Build contracts used on the case studies

All three case studies used Design and Build contracts. This type of contract follows very specific ways of working which govern the formal way that projects are managed and run. Design and Build (D/B) is a method of procurement where after sanction of a project all the design and construction services of a project are contracted to a single firm. The client has a contract with the so-called main contractor who is responsible for managing all aspects of the project once it has been sanctioned by the client. Prior to the D/B contract being put in place, the client engages the concept design team - usually consisting of an architect, design consultant and project manager (who is often the main contractor working on a fee basis in the initial stages). This team scopes out the project, agrees the initial design and develops outline costings. The client approves the design and then appoints the main contractor to run all aspects of the project from design through to construction and commissioning and handover. The concept design team may be novated to the main contractor, which means that they work on the project for the main contractor for the duration of the project. In some cases, rather than being novated to the main contractor, the architect and design consultant continue to work as independent client advisors, liaising closely with the main contractor (this was the case for Future Green and Synergy Court). The main contractor is responsible for detailing the design, appointing suppliers, managing the project and delivering the project on budget and on schedule (Gething, 2011; JCT, 2011).

5.3.6 **Formal project procedures applying to the case studies**

Each of the case studies was governed by similar formal procedures and systems. Building projects in the UK are often described in terms of the Royal Institute of British Architects (RIBA) model. These include: business justification (stage 1), feasibility studies (stage 2), project brief (stage 3), concept design (stage 4a and 4b), detail design (stage 5), production information (stage 6), mobilisation (stage 7), construction (stage 8), occupation and defects liability period (stage 9) and post-occupancy (stage 10) (Gething, 2011). Each stage has a defined set of outcomes and procedures and the responsibilities are clearly set out within Codes of Conduct and individual project files. Up to stage 6, the design team is usually comprised of the main contractor and its in-house design team, the project architect and a group of contracted consultants who advise, design and scope the project. During stage 6 the design team, under the direction of the main consultant, bundles up the project into work packages and sends them to suppliers for tender. It is at this stage that the project schedule or plan is drawn up. Formal procedures for each stage include contractual arrangements, agreement of tender documents, sign-off procedures on designs and drawings etc.

It is normal for the main contractor's firm to switch its representative during different stages of the project, so the project manager at concept design is likely to be a different project manager to the one at detail design and again during mobilisation and construction. As well as this fragmentation of personnel, the supply chain can be long and complex. Firms within the supply chain serve the main contractor or main suppliers, but also have their own ways of working and their own alliances and interests. The main contractor has a great deal of flexibility to interpret the stages and procedures and this freedom to orchestrate the project in many different ways parallels the bespoke nature of BIPV.

5.4 Analysis

Analysis of the data for each case study followed the same steps. After coding the interviews, SCOT diagrams were drawn up and a narrative written to reflect the different actor perspectives. Then an exploration of the technological frames and how they played out through the project was carried out. Following this, the co-development of the BIPV system and the building was examined and co-development diagrams were drawn up. The final stage of analysis involved exploring the data for issues about BIPV and the challenges which it poses for project teams.

The Coding of the anonymised transcripts used the provisional coding developed from the pilot study, which was further refined as coding and analysis continued. A full list of nodes used is set out in Appendix A4. One particular area of coding which emerged was the previous relationships between project actors, which seemed to affect decision-making on the projects. Additional codes were added to take these factors into account.

As the interview data was being coded, consideration was also given to the technological frames which had been developed from the pilot study. It became clear that these were not adequate to describe the full range of perspectives being recounted in the interviews. As a result, two extra technological frames were added: Time Sentry and Risk Minimiser. The Time Sentry's main interest in the inclusion of BIPV on a project was to ensure that the project was not delayed by any part of the BIPV system. The Risk Minimiser was concerned to prevent any risk in terms of contract breach, warranty invalidation or system operation arising from the incorporation of BIPV into the design. Table 5-6 gives an updated table showing the main interests of all of the technological frames. Appendix A3 gives a more detailed account of each frame.

Technological Frame	**Main interest of Technological Frame**
Design Aesthete	BIPV is part of the building which is a flagship architectural design
Green Guardians	BIPV reduces carbon emissions of the building and meets planning requirements
Design Optimiser	The process of design is efficient
Generation Maximiser	The PV system generates to its maximum potential
Cost Watcher	Project costs are kept to a minimum and financial case is maintained
Users	The system is fit for purpose and the generation does not negatively impact facilities management.
Time Sentry	To keep the project running on time
Risk Minimiser	Prevent risk in the form of warranty claims, broken contracts or poor performance

Table 5-6: Additional Technological Frames

For each case study, starting with a project stage (initial design, pre-tender design, tender, detail design, installation etc.) a search was made using the NVivo software and all examples of problems which occurred during that stage were identified. SCOT diagrams for each stage were then constructed, with consideration given to those artefacts, technological frames, problems and solutions which had been discussed in the interviews.

As analysis proceeded, it became clear that the constitution of technological frames changed over time and that adding a note of which actor mobilised which frame at each time would allow for exploration of this dynamic. In a departure from the recognised outline method (Bijker, 1999), technological frames were used in SCOT diagrams rather than the more usual RSGs and the actors within each of these frames at any moment were also noted. Each project stage was covered, until a complete map of the project had been drawn and all the interview data on problems and solutions had been included. Using the multiple actor perspectives from the SCOT diagrams, the narrative of the project was then drawn together and illustrated with extracts from the interviews.

Once the SCOT diagrams had been drawn, a detailed exploration of the composition of the technological frames started. This included developing an understanding of which actors were part of which frame at any time in the project, noting which technological frame or frames were involved in particular problem solving, and which frame was dominant at any one time. This analysis of the shifting nature of the groups and their inter-relationships formed one of the main parts of the research findings.

As the research question was to explore “how the mutual articulation of a building and the technology develop as BIPV is incorporated within a building”, the SCOT diagrams were considered in this light and co-development drawings were constructed, showing the changes made to the building and the BIPV system and the relationship between the two. One of these diagrams was developed for each case study. The method of development of these diagrams was experimental, but the format decided on is illustrated in Figure 5-4, where the first shaded horizontal line of boxes represents stages of the building development and the second shaded line of boxes represents changes to the BIPV system. The lines between them show the relationship between the two, whilst the white boxes mark key moments or outcomes in the project.

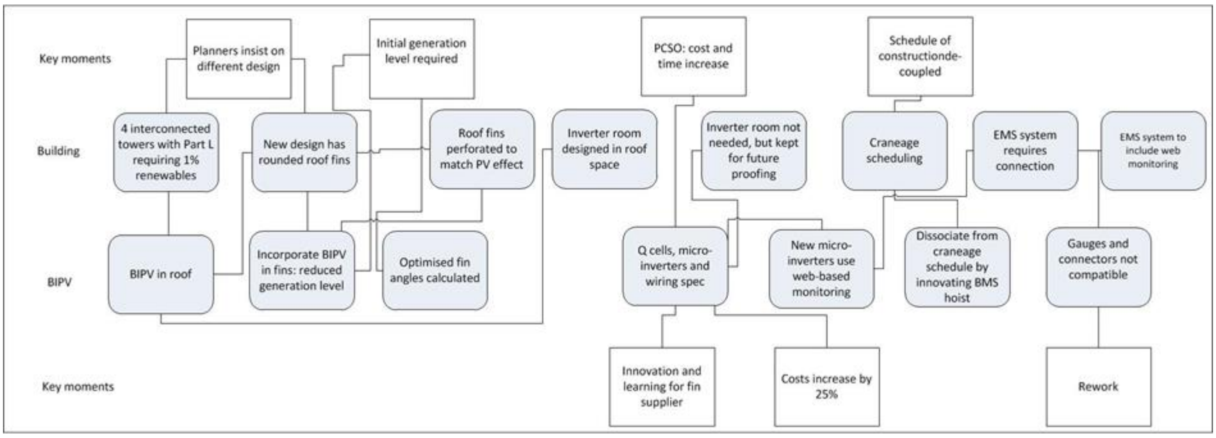


Figure 5-4: Example of a co-development diagram

Each project co-development drawing was studied and then broken down into discrete "episodes" of the co-development story. These episodes were drawn out in greater detail and analysed so that the types of co-development and the decision-making process which led to this co-development could be understood.

The final part of the analysis was to look at the data with a view to identifying issues about BIPV and the challenges which it poses for project teams. Each case study offered examples of challenges which had particular relevance for the construction sector and especially for the standard procedures and practices encountered in construction projects.

5.5 Cross case analysis

The purpose of this research is to explore how the adoption of technology is a dynamic process between the local context, the actors and the technology. Using SCOT to analyse the three case studies allowed a micro-level analysis of what occurred during the incorporation of BIPV within each project. SCOT does not allow for any comparison of similarities or differences in processes, mechanisms and outcomes which might inform an understanding of the process of adoption of technology. To achieve this level of abstraction, a cross case analysis was carried out to explore the levels and types of integration occurring and the dynamics of adoption and co-development. These two themes merged from the literature review and data from individual case study analysis.

The case study data was re-analysed to identify factors of each case which might account for differences in integration in terms of technology integration, team integration and process integration. This re-analysis was repeated to identify elements which might account for the dynamics of adoption in terms of the technological frames mobilised, the decisions taken and the types of co-development that took place within the case studies. Together these comparisons brought into focus an understanding of some the mechanisms which occurred in the process of the adoption of BIPV in projects, and used these to consider stabilisation mechanisms and uses these to consider stabilisation mechanisms which fixed particular design features of both BIPV and the building.

5.6 Limitations of the research design and blind spots

When reaching conclusions in research it is as important to understand what the research will not show as it is to present what it does show. These limitations can be considered in terms of “blind spots” of the theory used, limitations in the research design and “blank spots” (Wagner, 1993. p17) or deficiencies in the research data or population included in the research.

SCOT provides a framework to look at the unfolding development of a technological assemblage in terms of the artefacts, the actors, their frames, and the problems and solutions which occur. It is a micro-level approach which does not consider the firm level or institutional contexts within which the research takes place. One of the major criticisms of the approach is that power relationships, economic and intellectual reasons for choices, and cultural factors are not taken into account (Winner, 1993). In terms of this research these criticisms imply that the effects of economic policy, firm level strategy and contractual relationships between firms will not be taken into account. Careful consideration of the technological frames to some extent mitigates the effect of these blind spots (Klein & Kleinman, 2002), but the purpose of the research is to explore the process of adoption and as such it merits a fine grained approach, rather than a broader institutional study.

Limitations in the research design spring from two factors. Firstly, the research relied on actors' accounts to identify the relevant networks and events in the case studies. This subjectivity means that some perspectives may have been missed because some relevant actors may not have been interviewed and some events may have been glossed over in the accounts of the case studies. This limitation is addressed to an extent by the snowballing technique, which tries to pick up all the actors mentioned, but some accounts will inevitably have slipped through the net. Second, the research relies upon the researcher's subjective assessment of the interviews and documents, her individual perceptions of what happened and what was important. The narrative developed is a patchwork of different accounts given at different times with individual bias. Whilst this subjectivity is a feature of the approach, it does mean that checks or counter-balance in the form of a second point of view in coding and analysis were absent. Documents presented at interviews were used to support the accuracy of the narrative and to ensure that technical details were correctly presented.

Finally, deficiencies in the research data or population should be considered. As has been touched on above, finding the research population relied heavily on the nomination of actors by interviewees. Given the rapid turnover rate in the construction sector and the way that actors join and leave firms or projects, it was not possible to interview or contact all of the actors mentioned in interviews. Sometimes the interviewees relied on historical memory passed on by predecessors and sometimes there were just blank spots in the data, when no one could remember the exact sequence of events, or all of the possible solutions that were suggested at the time. Similarly, often because of inter-firm issues of confidentiality documentary evidence in the form of meeting minutes and evidence of specification or drawing revisions were not generally available. These would have served as corroborative evidence to support accounts and fill in any gaps. It was not possible to interview the tradesmen involved in the project and so the accounts from this particular front-line population are also missing from the data. Despite these limitations, the number of actors interviewed for each case study and the broad level of agreement between the accounts would suggest that the data can be relied on and is as complete as practical.

5.7 Ethics

This research was conducted in line with the University of Reading’s Code of Ethics. Prior to data gathering, the research design and methods were approved by the School of Construction Management and Engineering Research and Ethics Committee. Sample information sheets and interview consent sheets were submitted and procedures for processing and storing data were approved. Sample consent sheets and information sheets are included in Appendix A5.

Prior to interview all participants were fully informed about the purpose of the research and were given an information sheet to read and a consent form to sign (Appendix A5). All interviewees were given the opportunity to view transcripts of interviews and redact any parts they were unhappy with.

In line with the Code of Ethics, all data was anonymised immediately after transcription and before uploading into NVivo. Case study names were chosen to hide the identity of projects, firms and individuals. Direct quotes in papers arising from the research were attributed to formal roles, rather than company positions (for example: Architect rather than “Executive Partner, Architect”; or PV laminate supplier rather than “Area Sales Manager”) and all firms and contacts mentioned in the interviews were also anonymised.

The impact of the interviews on the participants in terms of risk, balance and mental health were assessed as part of the ethics approval procedure. No direct or indirect effects were identified. All data was treated in line with the confidentiality and storage requirements which form part of the ethics protocol. Data was stored securely either in a locked office and filing cabinet or on a password protected computer.

Chapter 6: Case Study - Vogue Terrace

This chapter presents the first case study (Vogue Terrace). After a general description of the project, the chapter then breaks down the case study into five key episodes which dominated the interviews: initial scheme; pre-tender and tender process; detail design; wiring; and installation. For each episode the chapter provides a narrative account of what happened, focusing on the succession of problems and solutions, reflecting on the changing technological frames of the actors, and exploring the co-development of the building and the BIPV. The chapter goes on to summarise the way that actors mobilised different frames at different times throughout the project, and explores the mechanisms of co-development between the building and the technology. Finally the chapter summarises the issues and the challenges which the project team faced as BIPV was integrated within the project.

6.1 Description

Vogue Terrace is a commercial office building and forms part of a three phase refurbishment project in which three adjacent office blocks were reduced to a skeleton and then effectively reconstructed. The phased development started in the mid-2000s with Vogue Terrace being the last of the three blocks to be constructed. Initial planning permission was granted in 2007, but the project was mothballed during the recession which began in 2008. Work began again in 2012, with tenders for the major contracts going out in early 2014. Work on site began in August 2014, with work on the BIPV installation commencing February 2015. BIPV was integrated into 672 brise-soleil louvres on the south elevation of the building. The BIPV system was thought to generate around 70kW peak.

The project used a "Design and Build" contract, with the client stipulating that the same design and construction team was to be used on all three projects. Some of these project personnel were named in the client contract (in particular the main contractor's M&E design manager).

Interviewing took place over a two and a half year period, starting before construction with one interview with the PV panel supplier and three interviews with the architect. This was followed by eight interviews with members of the project team during the construction period. Chapter 5 (Methods) gives detailed information about those interviewed. In the following analysis interviewees are referenced by the firm they represent: architect (MH); main contractor (WR); M&E design consultant (DC); façade supplier (QC); façade consultant (WH); PV wiring contractor (DEP); and PV laminate supplier (LE). The PV laminate supplier (LE) is a different company to the BIPV supplier (Myd). A number is added to the reference as a unique identifier for each actor in the firm (for example: "main contractor (WR01)" represents the main contractor firm - WR, and is the first actor interviewed from that firm. "Main contractor (WR02)" indicates the second person interviewed at the main contractor firm).

6.2 Episode 1: the initial scheme

The first episode covers the development of the concept design for the building to the point that the work packages for tender had been developed.

6.2.1 Episode 1: narrative account

The client commissioned a phased development of three adjacent properties. To meet the local authority planning requirements for renewable energy, and as part of the client's commitment to carbon reduction, the client, architect (MH) and design consultant (DC) developed a sustainability strategy for the three buildings and this was agreed with the planning office. The client and architect (MH) insisted that the sustainability strategy be based on an integrated mix of technologies. The strategy included the provision of PV, a ground source heat pump and several other sustainable features (chilled beams, air filtering, LED lighting etc.). Planning permission was granted on the basis of a coherent development plan which included the use of PV on the project. At this point, in keeping with the early stage of the project, the technologies and building itself were considered in schematic form, with the technology being thought of as little more than "black boxes" within a broad design.

The architect (MH01) illustrated this black-boxing of technologies when he explained how in the initial phase of the project the design team were unaware of the implications of the sustainability strategy.

> The planning condition is tied to the proposal of renewables rather than a figure….there is a figure in there, but I think if somebody challenged it we'd have a lot less on the building, just because at the time I don't quite think everybody knew exactly what it meant to have 10% renewables.
>
> Architect (MH01)

In 2007, following the successful completion of the first two phases of the development, the client wanted to ensure that the third phase proceeded as successfully as the other two (both in terms of efficiency of construction and the aesthetics of the final development) and insisted that the same project teams and major contractors be involved for the final phase (including the architectural practice (MH) and the façade supplier (QC)). In some cases named individuals were requested (WR01). None of the individuals who were nominated to the project had prior experience of BIPV.

> They told us that they would like to go back only to the people which they worked [with] before, without competition. Obviously the price has to be right, otherwise they open up the competition to a wider field
>
> Façade supplier (QC01)

> As part of the contractual deal that we did with the client, where possible, members of the original team were asked to come back and complete [Vogue Terrace], so that's how I got involved in it.
>
> Façade consultant (WH01)

Although the project team for the third phase was appointed in 2007, the project was then mothballed until 2012 because of the recession. During this time the client considered various options for the building to realise an economic return. One was the conversion of the site to residential and student housing, but as the area was considered by the architect (MH) and planners to be unsuitable for residential development, the original plan for a commercial building was retained. On re-opening the project in 2012, the client was concerned that the design remain current, and as part of the design review the architect (MH) suggested using PV cells in the external brise-soleil louvres on the south elevation of the building. This had the advantage of using a technology which was already included in in the sustainability strategy, while also bringing an element of contemporary design. The use of BIPV in the brise-soleil louvres became a central element of the external modern look of the building. The purpose of the PV brise-soleil was encapsulated by the façade consultant (WH01).

> Vogue Terrace was a "stop and start" 3 times. I think on the rear elevation…it's about adding interest to the building more than anything else. Did it deliver anything else? No, not really. The glass, the design of the glass, the development of the façade did everything it needed to do. It did all the solar shading …heat gain, heat loss - that was all managed with the glass in the system.
>
> Façade consultant (WH01)

The architect (MH) had no experience of using BIPV, but worked extensively with the PV laminate supplier (LE) to establish a viable proposal. The PV laminate supplier (LE) was keen to discuss the design with the architect (MH) to develop the potential business, but at the same time steered clear of any detailed work, as he was aware that his firm might not be awarded the contract and was not paid for this initial work. It was at this point that the architect (MH) first became aware that BIPV was a system with many interconnected technologies and focussed on the PV panels, the frame into which they would fit, the way that wires would enter the building and the location of the inverters. During discussions with the PV laminate supplier (LE) the architect (MH) realised that the users of the building would see an unsightly grid of grey PV cells on each louvre. In response to the architect's concerns about this, the PV laminate supplier (LE) offered the possibility of a white glass interlayer to improve the aesthetics. As the design moved from outline to more detailed design the design input from the PV laminate glass supplier (LE) reduced because of the uncertainty of winning the tender.

During the initial design stage, a mechanical and electrical design consultant (DC) carried out a rough sizing of the BIPV system by calculating the number of louvres that would be installed on the elevation of the building. This design specified the number of brise-soleil louvres, the spacing of the cells within the louvres and the number of inverters required. Prior to agreeing the initial design, the client, architect (LE) and main contractor (WR) carried out a review of project costings and found the project to be over budget. A Value Engineering (VE) exercise took place and the PV panels were identified as a significant cost item. The architect (MH) and client were intent on keeping the BIPV to keep the building up to date and to keep the sustainability strategy on track. The compromise made was to squeeze an additional two PV cells into each louvre and so reduce the total number of PV louvres without compromising the calculated generation potential of 70kW peak. The client decided to reduce the finishes specification on the internal fixings, rather than get rid of the PV louvres. This was highlighted by the architect when talking about the Value Engineering exercise.

> Without them being the client that they are, it wouldn't be there. So they bought into it, and they're now insisting on having it. So much so that when the contractors were pricing the scheme to build it, it was coming in over budget, and [the client] said well we're not changing the photovoltaics, so the money went out of finishes, which was a good step.
>
> Architect (MH01)

The discussions between the architect, PV laminate supplier (LE) and M&E design contractor (WR) were based on costs and the number of PV brise-soleil louvres, rather than how the electricity generated by the BIPV system would be integrated with the mains electricity supply. The architect developed a scheme for the wiring from the PV cells which involved penetrating the façade through the window seals and running through the landlord riser to inverters sited by the lift shaft. A major consideration for this decision was that the wiring should be invisible from the outside - the architect (MH) had concerns that the clean lines of the building should not be spoilt by visible external wiring wires and that the wires would sag if the cable runs were of any significant length. The number and exact siting of the inverters was undecided and this meant that the wiring runs and floor plans were left open - the situation was summed up by the architect during the first interview.

> Any riser space is premium, so we'd like to have as few inverters as possible. If he came back and said oh, I need one every four floors, and it's that big and we can put it in there, that would be great. But we think he's going to come back and say I need two every floor, where can they go? And they'll want to be in some random place. But that process has to happen, it's unfortunate that there was nobody at the design stage to be able to give us that advice.
>
> Architect (MH01)

At this point the initial design was stabilised as the basis for appointing a main contractor (WR) and drawing up tender documents. Given the delays on the project the client was keen to move forward and the main contractor (nominated by the client because of their involvement in the previous two phases) proceeded to draw up the work packages for tender. Neither the architect nor the main contractor was familiar with PV design so the detail of the layout and specification for the PV system was very loosely defined.

The architect (MH) worked with the PV laminate supplier (LE) to optimise the spacing of the PV cells in each louvre in terms of the aesthetics of each panel. The architect felt it important to have even an spacing of the cells with a precise margin of clear glass around the edges of the panel. The PV layout was included in a two-page specification which was used by the main contractor as the basis for the tender document for the PV system. The discussion around the BIPV system focussed on the aesthetics and design layout, rather than its generation potential. This emphasis was underlined by the façade consultant (WH).

> Once LE got involved, it all became around what it looked like, how we were manufacturing it, how we were wiring it, more than what the output was.
>
> Façade consultant (WH01)

The list of contractors to be approached for tender was based on those used in the previous two phases of the development, as specified by the client. The main contractor (WR) divided work packages in a similar way to the previous phases. The PV system was included in the façade work package.

6.2.2 Episode 1: technological frames

This section illustrates how the actors viewed the technology through different frames throughout this episode and how tensions developed between the RSGs over conflicting goals. Figure 6-1 shows how the network of actors, technological frames, problems and solutions played out during the initial design episode and the following description draws attention to the main highlights of the episode

Chapter 5 (Methods) outlined the six distinct technological frames which were identified through the pilot study (Design Aesthete, Design Optimiser, Green Guardian, Generation Maximiser, Cost Watcher and User). Two further frames (Time Sentry and Risk Minimiser) were added during the analysis. Over the course of the project, the actors unwittingly mobilised these technological frames as they negotiated the problems and solutions on the project.

At the start of the project the architect (MH) and client saw the project through the Design Aesthete frame as they developed a cohesive three stage design plan for the site. Both the local planning representative and the client took on the Green Guardian frame, as they were concerned with ensuring that the building included sustainable technology and that there was sustainability strategy for all three buildings. The architect (MH) also adopted the Green Guardian frame to develop sustainable solutions for the buildings - including a ground source heat pump, chilled beams, LED lighting and the use of PV power. After the project had been mothballed for four years, the client and architect (MH) reviewed the project and mobilised the frame of the Design Aesthete, amid concerns that the building should not look dated. They viewed BIPV as an integral part of the building identity, making a positive contribution to the design aesthetics of the building. The client mobilised the Risk Minimiser frame to maintain the team that had delivered the other two phases of the project, and so locked-in the supply chain. As the initial design got underway the M&E design consultant (DC) mobilised the Generation Maximiser frame as he tried to maximise the PV generation of the system by fitting as many cells to as many louvres as possible on the south facing façade and sizing inverters to match the system.

Just before the initial design was signed off by the project team the final cost estimate was drawn up by the main contractor (WR). Viewing the project through the frame of the Cost Watcher, the client and main contractor called for a value engineering exercise to reduce costs. During this exercise attention was drawn to the cost of the BIPV system and the main contractor (WR) proposed that the system be dropped from the project. Using the Green Guardian frame, the client refused to follow this option, and instead chose to reduce the indoor finishes specification on the building, whilst maintaining the commitment to sustainability. The architect (MH) adopted the Generation Maximiser frame as he worked with the M&E consultant (DC) to reduce the number of PV louvres on the façade and increase the number of PV cells in each louvre. He also adopted the Green Guardian frame to work within the BREEAM guidelines to achieve an “excellent” rated building and to fulfil the planning authority requirements of the sustainable strategy for the project.

Although the PV laminate supplier (LE) normally viewed the technology through the frame of Design Optimiser, he worked intermittently with the architect (MH), using the Design Aesthete frame to develop a workable, symmetrical cell layout on each louvre, and offered to provide a white interlayer to improve the appearance of the louvres to the occupants of the building. Figure 6-1 summarises the changing pattern of problems and solutions as the initial design progressed and shows how the technological frames were mobilised by the actors.

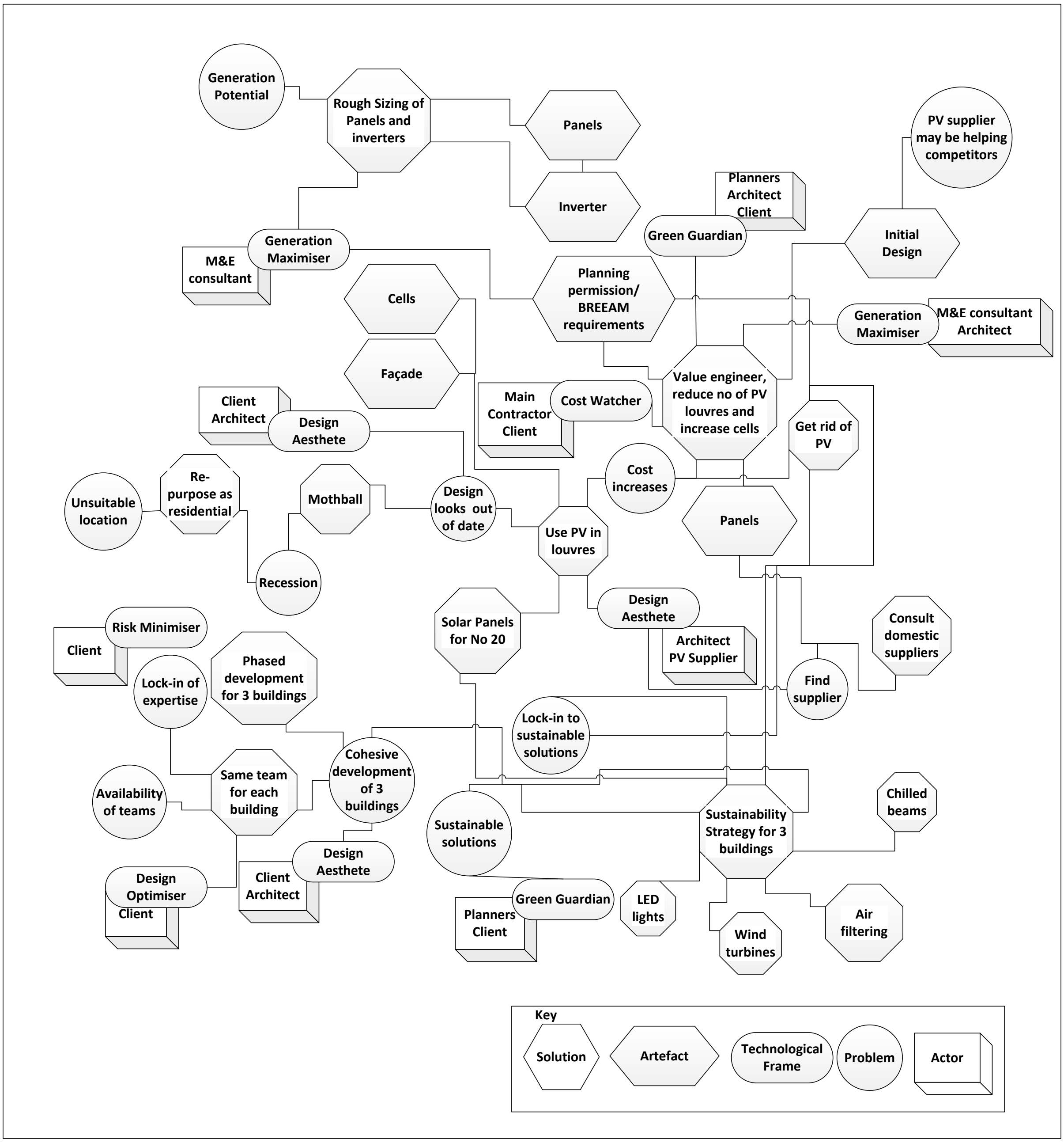


Figure 6-1: Technological frames mobilized in episode 1 (initial design), Vogue Terrace

The analysis above illustrates how the various technological frames were mobilised by the actors during this episode and that many of the actors related to the technology through more than one frame. The analysis also demonstrates how conflicting goals between actors using different frames gave rise to problems and how solutions were developed through different mechanisms. The following examples illustrate these points.

- One particular frame was established as the dominant frame which drove the solution (the Green Guardian frame became the dominant frame when the client decided that BIPV had to be included in the design).
- The design was revised to accommodate multiple frames (the revised design satisfied both requirements by cutting costs and satisfying the sustainability strategy).

6.2.3 Episode 1: co-development

This first episode illustrates how rather than the BIPV or the building being fixed, the BIPV system accommodated the building and vice-versa. The summary of co-development during the whole case study is presented in section 6.7.2, but three important elements of the co-development of building and technology occurred in this episode of the project.

i. The early decision to use BIPV as a very visible statement about the modernity of the building, and the inclusion of PV technology in the sustainability strategy for the project, led to the privileging of BIPV over the standard of finishes in the building specification.
ii. The decision to use the same supply chain for Vogue Terrace as for the previous two phases locked-in the expertise available for the development of the BIPV system.
iii. The architect’s desire to ensure that the wiring could not be seen externally complicated wiring runs.

6.3 Episode 2: pre-tender and tender

The second episode follows from the initial design, where the use of BIPV as brise-soleil louvres had been agreed and the supply chain for the major building contracts had been determined. The pre-tender and tender episode follows the development of the detailed system and building design, and begins after the pre-tender design team had carried out a value engineering (VE) exercise to reduce project costs.

6.3.1 Episode 2: narrative account

The client-nominated façade supplier (QC) received the tender package and, together with the façade consultant (WH) (who had also been involved in the first two phases and was novated to the main contractor to liaise with the façade supplier), considered the PV element of the work package. Although the façade supplier (QC) had occasionally dealt with roof mounted PV systems, the firm had no experience of BIPV and was concerned about the effect on water and air tightness of penetrating the façade with wiring. The façade supplier (QC) had initial discussions with two PV laminate suppliers to scope out the bid. The façade supplier was prepared to use the quote from one of them (LE) as part of their bid, but was not prepared to consider the wiring or inverters as part of the package. This reluctance was summarised by the façade supplier

> That's why we said that we don't want to get involved in that, because otherwise we would need some kind of an electrical engineering assistance to check on that…and that's not something which we wanted to get involved in.
>
> Façade supplier (QC01)

Ultimately the façade supplier (QC) declined to include the PV system within their package. The main contractor (WR) discussed the decision with the façade consultant (WH), who supported the façade supplier (QC) in their decision. The architect (MH) was uncomfortable with this decision, but the main contractor (WR) was comfortable that the façade and PV packages could be de-coupled.

The main contractor (WR) had recently acquired a subsidiary (Myd) which had a PV business and because of this decided to take the PV system out of the façade contract and to appoint

Myd as the BIPV supplier. The main contractor (WR), architect (QC) and BIPV supplier (Myd) discussed the PV package and identified five main issues: the type of cells used; how to get the wires from the cells to the inverters; how to group the wire; how to connect up the system in terms of strings; where to site the inverters; and how many inverters would be needed. The BIPV supplier (Myd) was keen to substitute the monocrystalline cells with the cheaper alternative of polycrystalline, in order to reduce costs and increase their profit margins. However the architect (MH) was insistent that monocrystalline technology was used as polycrystalline cells had a lower efficiency. This interplay was described by the architect in his second interview.

> They're trying to rationalise this, because the first question this guy asked is well, we'll just use the polycrystals, and we said well, why? And he said oh, because they're cheaper, but we didn't want cheap ones, we wanted the monocrystals, because they're a lot better quality. And he said yeah, but nowadays they're so close. And we said well, but are they the same? And he said no, the monocrystals still do have that little bit of quality, but it's marginal. I said well, over 672 times, there's 22 cells per louvre, times 672, so anything that's marginal, is big.
>
> Architect (MH01)

The BIPV contractor (Myd) suggested that two inverters per floor would be needed in the landlord riser, but the main contractor (WR) was unhappy with the space that this number of inverters would take up in the already congested riser. The architect (MH) was concerned that the wires would not detract from the aesthetics either internally or externally and came up with several designs where the wires would penetrate through the bracketry or through the join line of the glass in each bay of four louvres. The main contractor (WR) and PV laminate supplier (LE) were interested in minimising costs and wanted to run the wiring horizontally across the façade, penetrating the façade at just one point. Because of the relatively low cost of the PV system (compared to the total project cost) and because of the in-house relationship between the main contractor (WR) and the BIPV supplier (Myd), the detailed design issues remained unresolved and Myd was left to develop the design. The main contractor (WR) assumed that Myd had the necessary expertise to deliver the design and install the system. This in-house relationship was described by the main contractor (WR) as follows:

> At the time we owned a chunk of that [Myd] so I think where we were sitting there feeling all blasé and thinking well, we own a company who does this, it's going to be a piece of cake.
>
> Main contractor (WR02)

After these discussions the BIPV supplier (Myd) became very hard to reach and no design information was made available. In the intervening weeks the BIPV supplier (Myd) was sold by the main contractor (WR), but the main contractor still expected the PV system to be supplied by Myd. Finally the BIPV system designer at Myd contacted the main contractor (WR) and said that he was leaving the company. It became clear to the main contractor (WR) that Myd would no longer provide the PV system. This put the PV system behind schedule and rather than risk further delays, the main contractor (WR) made the decision to split the PV procurement into two parts - the panels and the electrical system. This decision was made to keep the project schedule on track. As the schedule was pressing for the PV panels to be procured and fitted to the façade brackets, the main contractor approached the original PV panel supplier (LE) to ask for a quotation for the panels. The electrical part of the PV system was put on hold, as the main contractor (WR) considered that it was non-critical and could wait until later in the project to be designed and procured.

> Façade design is complex and complicated; second to M&E this is the second biggest package on any job. So they always want to procure M&E early and they always want to procure the façades early.
>
> Façade consultant (WH01)

The laminate panel supplier (LE) quoted for the panels and as the cost for these was much lower than the package price from Myd, the main contractor decided to increase his profit margin by "free issuing" the PV panels to the façade supplier (QC), and to use the façade consultant (WH) as an intermediary between the PV laminate supplier (LE) and the façade supplier (QC). The driving force for the decision was a financial one for the main contractor (WR), but the decision also suited the façade supplier (QC). This situation is illustrated in the following extract.

> It was implied that QC would be quoting it and QC made it quite clear they didn't want to do all that...And it was financially beneficial for...we're trying to get some benefit in the end. I mean it was a matter of getting a price for the job that the client could say, yes I can commit to that.
>
> Main contractor (WR02)

The façade contract was changed to include all the bracketry and frames for the PV louvres, on the understanding that the laminated PV panels would be supplied as "free issue" to the façade supplier (QC).

6.3.2 Episode 2: technological frames

The following analysis illustrates how tensions between actors with different technological frames led to conflicts. Figure 6-2 shows how the network of actors, technological frames, problems and solutions played out during the tender episode and the following description draws attention to the main highlights of the episode

In line with the client's requirement, the main contractor (WR) drew up the tender packages and issued them to the previously agreed supply chain. The BIPV system was included within the façade supplier's package (QC), even though the façade supplier had no experience of BIPV other than roof-top (BAPV) installations. Looking at the work package through the

Design Optimiser frame, the façade supplier (QC) was concerned that the PV design was unfamiliar and began to investigate ways to accommodate wiring without risking the integrity of the façade. Concerned with unknown costs (Cost Watcher frame), unfamiliar technology, and problems of integrating it without risking weather-tightness (Risk Minimiser frame), the façade supplier (QC) refused to include the BIPV system within the package. It is interesting to note that the tender document itself (in the form of a contract) played an important part in making clear the potential risks of agreeing to supply the BIPV system and in the façade supplier's decision not to include the system in their quote.

The main contractor (WR) accepted this refusal both because the client had insisted on the façade supplier as part of the project contract and also because it was an opportunity to reduce costs by appointing a BIPV supplier (Myd) who was a subsidiary to the main contractor company (Cost Watcher frame). The BIPV supplier (Myd) agreed to take the work package and worked through the Design Optimiser frame to develop solutions to get the wires inside the building, to determine the sizing of inverters and to decide where to site them. The architect (MH) had concerns over reducing the visual impact of the BIPV wiring (Design Aesthete frame). Conflict arose when the BIPV supplier (Myd) wanted to reduce the specification of the technology to polycrystalline cells (in an effort to reduce costs). The architect (MH) was sufficiently invested with the Generation Maximiser frame to insist on monocrystalline cells and refused.

Once the BIPV supplier (Myd) disengaged from the project, the main contractor (WR) was concerned about the project schedule (Time Sentry frame) and made the decision to decouple the BIPV system by "free issuing" the PV louvres to the façade supplier (QC) and putting the electrical work for the BIPV system into a new work package to be sent out to tender with wiring contractors. One other factor in this decision was to reduce costs by dealing directly with the PV laminate supplier (LE) and free issue the PV panels to the façade supplier (QC), thereby improving profit margins. This combining of the Cost Watcher and Time Sentry frames forced a decision to be taken which had huge impacts on the delivery of the BIPV system, with very little consideration of the consequences.

This episode is characterised by a series of tensions which arose when an actor viewed the technology through multiple frames - the façade supplier (QC) saw the BIPV both as a potential source of profit, but also as source of risk. The main contractor (WR) saw the BIPV contract as a problem with regard to time and as an opportunity to reduce costs. It is interesting to note that in both cases decisions were taken in isolation from other project actors and this “silo-ing” effect obscured the full implications of these decisions on the project.

During this episode there were very few instances when actors from one frame could see the technology through other frames and could then present their ideas in such a way that it became acceptable to those using other frames. This marks a characteristic of the project - it was run generally as a series of separate tenders, with very little understanding of how the various tender packages were connected. The analysis above illustrates how the Cost Watcher, Time Sentry and Risk Minimiser frames had a particular influence on non-collaborative decision-making during this episode even though the artefacts they represent are not physically present. The analysis also demonstrates how technological frames can explain how conflicting goals between actors using different frames gave rise to problems and how solutions were then developed through different mechanisms.

Figure 6-2 summarises the changing pattern of problems and solutions as the initial design progressed and shows how the technological frames were mobilised by the actors.

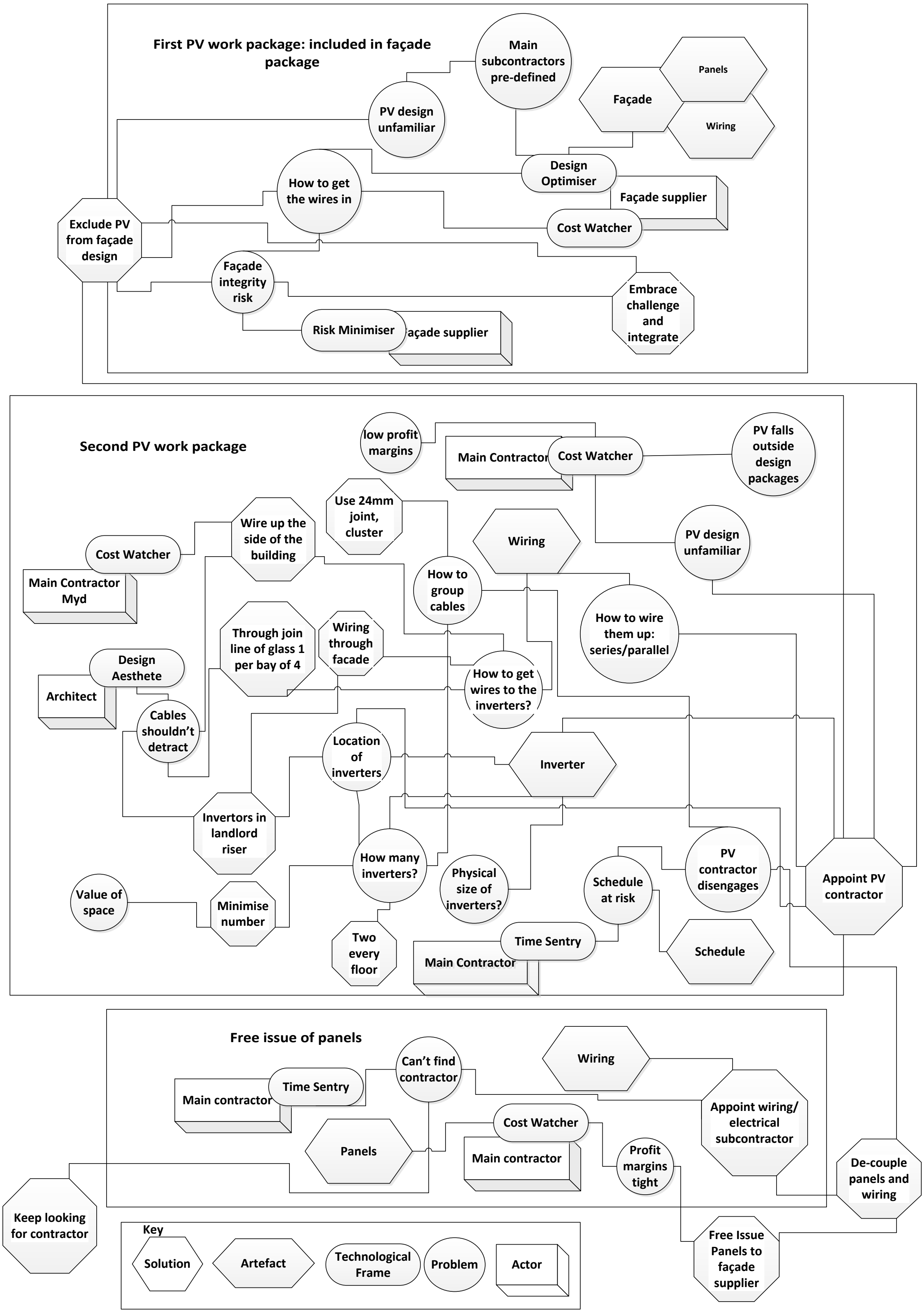


Figure 6-2: Technological frames mobilized in episode 2 (pre-tender and tender), Vogue Terrace

6.3.3 Episode 2: co-development

During this episode of the project, four elements of co-development between the building and the BIPV system were apparent - two were process related and two were design related.

Process

i. The refusal by the façade supplier to include the BIPV system in the tender for the building façade work package led to the de-coupling of the BIPV system from the building façade contract.

ii. The decision by the main contractor to de-couple the elements of the BIPV system into free issue louvres and an electrical system meant that the BIPV was not designed as an integrated system, rather as a series of disparate parts. This had major implications for its design, installation and performance.

Design

iii. The need to include BIPV wiring within the frames and brackets led to a re-design of all the brise-soleil louvres on the south elevation of the building - whether they were PV louvres or not.

iv. The façade supplier’s refusal to allow the BIPV wiring to penetrate the façade by each louvre, because of the risk to the integrity of the façade, meant that the wires for the system had to run along the external cladding and then penetrate the façade at each floor in order to be connected the two inverters. The result of this co-development was that the wiring would be visible and that increased length wiring runs at low voltage would increase system losses.

6.4 Episode 3: detail design

This episode starts when the work packages had been scoped and the decision taken to free issue the PV laminate panels to the façade supplier (QC).

6.4.1 Episode 3: narrative account

This episode focusses on three detail design issues which involved the BIPV system. These were; glass thickness and notching; white laminate interlayer; and frame and bracket design. These three elements of the design brought the co-development of the building and BIPV system into focus. An account of the development of each of these issues is presented.

Glass thickness and notching

The original specification to the PV laminate supplier (LE) was for 672 louvre panels of laminated glass, 5mm thick, with an interlayer of white laminate and monocrystalline cells. Each panel was to fit into a 3-sided frame, to give the effect of the louvres floating out of the façade with no visible front edge. Each glass panel was to have a notch in the centre of the rear long edge to allow for a good key when fitting the glass to the three sided "razor blade" frame. However the façade supplier (who was making the frames) offered a bonded joint between the frame and glass to reduce the complexity of the frame, but which would make the bracket slightly thicker. This option was accepted by the main contractor on grounds of cost and time savings and the architect reluctantly agreed.

The façade supplier (QC) submitted drawings for the frame to the main contractor (WR) and architect (MH) for approval of the extrusion design for the frames. The architect (MH) was concerned that the louvres might bow and spoil the aesthetics of the building. This had happened to the non PV brise-soleil on the adjacent buildings and he was keen that this should not happen again, particularly as the PV panels were heavier than those used in the adjacent buildings. The façade supplier (QC), main contractor (WR), PV laminate supplier (LE) and façade consultant (WH) were all concerned on different levels that they might become liable should bowing occur and each made a set of calculations based on different methods, each of which suggested different glass thicknesses. The façade supplier (QC) suggested redesigning the frames to a "picture frame" design, so that the glass would be supported on all sides and minimise the risk of bowing. The main contractor (WR) felt that this would increase the cost of the frames and the architect maintained that this was outside the agreed design in terms of aesthetics and the planning permission (although the planners were not approached to give a view on this). The main contractor (WR) had no desire to revisit planning permissions, both because of time constraints and because by that time the renewables requirement from the Borough Council had changed and new planning permission would possibly require re-visiting the renewables strategy on the building. The picture-frame idea was therefore rejected and the original "razor blade" frame was retained.

The main contractor (WR) was unsure whether to insist on 6mm glass laminate to address the issue of bowing glass and at the same time the architect (MH) had raised concerns over glass strength on impact. The main contractor (WR) therefore commissioned a series of impact test calculations to be undertaken. The issue of risk and responsibility became heightened, with the PV laminate supplier (LE) requesting sign off of the specification, and different firms carrying out different calculations. This situation was resolved when the PV laminate supplier (LE) offered to supply the glass at 6mm for no additional cost (it emerged subsequently that the PV laminate supplier had already decided, as company policy, to supply all laminates at 6mm thickness, so moving from 5mm to 6mm laminate on this project, made life simpler for them).

A result of this decision was that the façade supplier (QC) had to strengthen the razor-blade frame design to support the thicker and consequently heavier louvres. The change in frame dimensions meant that the PV laminate supplier had to adjust the spacing of the individual cells in the panel so that the frame did not shade the cells and reduce generation. The fragmented way that this issue was resolved is summarised by a discussion between the two main contractor team members (WR01 and WR02).

> We placed the order direct with LE, so to a large extent QC were out of the equation…. We had LE do some drawings for us which we then sent to the architect to say, are you happy with the sizes, that this fits into the QC system? Once he said, yes I'm happy with that. We then sent that to QC …and they overlaid their framework onto it with the containment on the back, and then at that particular stage we realised that the connections and everything were likely to be affected by the structure of the framework … So we then back to LE and said, can you adjust those dimensions by, I think it was about 20mm or 30mm.
>
> Main contractor (WR01)

> QC, they overlaid their framework that they knew, because they knew obviously that the PVs were coming, they'd already designed a framework and then it became clear by overlaying that that the connectors and the diode were not quite in the right place. So then go back to LE and say, right we need to move those in, any problems? No. Fine, done, move them in by that much. That drawing then gets sent for final approval. QC say, yes. We say, yes. Architect says, yes. Done.
>
> Main contractor (WR02)

Interlayer

The specification for the PV laminate panels included a white interlayer which was to be bonded onto the glass between the under-layer of glass and the PV cells. This had been offered by the PV laminate supplier (LE) as a result of discussions with the architect (MH) about the aesthetic appearance of the cells to office users. The aesthetic considerations for this design were outlined by the architect (MH).

> So in the office place they're looking at three or four of these, and, they're big -.so it, it's quite a large part of their view. Also, because of the solar shading element, we're going to look at a white interlayer. But what I want to do is make it about 80% so that you can still see the squares, so just because they're there, so you might as well make it look nice, or else it just looks like a painted plank outside.
>
> Architect (MH01)

As production of the laminate louvres began, the PV laminate supplier (LE) contacted the architect (MH) to inform him that the production process was causing the white interlayer to be speckled with very small, irregularly occurring dark spots where the interlayer fused to the glass in the annealing process. The PV laminate supplier (LE) offered two solutions: to continue with the process and accept the small spots (as they would be virtually invisible once installed); or to adopt a screen printing process which would give a more opaque finish, but which would be spot free. The architect (MH) discussed the options with the client and main contractor (WR) and they decided to accept a screen printed louvre.

Frame and Bracket

The PV laminate panels were to be shipped from the PV laminate supplier (LE) to the façade supplier (QC), where the louvre would be fitted into a frame and bracket assembly. This interface was under-scored by the architect:

> I'm trying to arrange a meeting with the cladding contractors, because they need to interface. So there's a buildability issue when this bracket goes through that mullion, who's fixing it, how is it being fixed? You've got…the cladding contractor is dealing with the unitised cladding, and the photovoltaics guy is dealing with that fixing.
>
> Architect (MH01)

The PV louvre, frame and bracket assembly would be packed into specially designed stillages and transported to site where they would be bolted directly onto the window just prior to installation. Each laminate PV panel had two electrical connectors and trailing electrical wires which had to be connected to the next panel and thence to the inverters. The architect (MH) had initially wanted the wires to penetrate through the frame and penetrate the façade seal at each window. The façade consultant (WH) had rejected this idea and proposed that the cables be run horizontally across each floor of the external façade, and enter the building in one location on each floor. In the following two excerpts the façade consultant (WH) summed up his view of the situation and the frustration of trying to resolve the issue.

> Its a lack of listening on the main contractor’s part sometimes. They don't listen when you tell them we're not penetrating the curtain wall all the way through. And you get the usual, well we've done it before, we've done it before, well yeah you have but you haven't done it on one of my jobs and I won't let it happen. So, and QC agreed with me, they wouldn't let it happen. So in the end a bit of common sense prevailed and [the client] are very good like that because they'll step in and say, no we don't want loads of cabling coming inside, if ever there's a problem, we’re disrupting tenants on floors etc, etc, it makes more sense to keep all the cabling outside, take all the inverters to the roof, there's plenty of room, put them up there.
>
> Façade consultant (WH01)

> I said that all the wires, floor by floor should run horizontally, outside, in tracks which was easy to do, to the end walls which are rain-screen, so there's a cavity of 300mm, straight up to the roof, no problem, across into the inverters wherever they're going to be. That for me was easy. Alternatively group them as groups…whether it be horizontal groups, or whether it be vertical groups, and run up in the same way.
>
> Façade consultant (WH01)

The architect (MH) was concerned with the idea of visible external wiring and with the possibility of sagging cables being seen and suggested an arrangement of frame and bracket where the wires were hidden within the frame and connected to the inverters through the mullion by the bracket holding up each frame. The façade supplier (QC) rejected the idea of penetrating the façade at each window, but accepted the idea of accommodating the wires within the frame and bracketry. The process of evolution of the frame was described by the façade supplier.

> When I start with the job it was already clear that the panels were not part of our package and that we should take care of the frame, and also study the way how to run the cables, In the beginning they were supposed to run in our joints, in the joints of our units, then we saw that is not a good idea, and then we developed together with the design team a special cable tray to run the cables inside in a way that was to have less visual impact.
>
> Façade supplier (QC02)

The main contractor (WR) decided to adopt the idea of incorporating the wiring within the bracketry, but sided with the façade supplier (QC) in running the wiring in horizontal groups externally. Considerations of buildability, reduced installation time and scaffolding schedules were key drivers for this decision. The façade supplier (QC) had to allow enough room within the louvre frames and brackets to accommodate the wires. The PV wiring contractor had not been appointed at this stage and so the diameter of the wiring, the connection types and the configuration of the strings were all unknown. This lack of detailing was highlighted by the façade supplier.

> But at that stage, that was at the tender stage, nobody knew the size of the cables, the amount of the cables, if it’s going to be one cable or three cables, ten cables, though it was a little bit in there.
>
> Façade supplier (QC02)

The architect (MH) and PV laminate supplier (LE) made best guesses of the wiring diameters and stipulated that the frames should not crimp the wiring and that the wiring should not be squeezed into tight turns and should not become too congested. The façade supplier (QC) had to specify the size of extrusions to be used in the frame and bracket and opted for larger bracket sizing to ensure there was enough room to take the wiring. This entailed more material usage and a more solid design, but the façade supplier (QC) was constrained by the lack of solid information with which to refine the design. Drawings were sent to the main contractor (WR), who passed them to the architect (MH) for approval. The architect (MH) refused to sign them off because the sizing of the brackets and frames could not be finalised until the wiring contractor had been appointed and had given the final sizing of wiring. This refusal began to put the schedule behind and the main contractor (WR) began to look for a wiring contractor in earnest.

Four months into the build the main contractor (WR) found a wiring contractor (DEP) who was willing to procure and install the electrical side of the PV system and he became involved in the final design of the system. Over 600 wires had to be incorporated into the design and the sizing of the brackets and frames were too small. The limitations of the outline wiring design became apparent as the new contractor came on board. The wiring contractor (DEP) summarised the situation in the excerpt below.

> "No, well, I don't know what the history of the previous PV installer was, but there was obviously somebody involved in design and I think specifying the right inverters for the job and giving them some idea of where they might go and possibly where the wires might go. But it was very sketchy, and not a very good design when I picked it up...They asked me to go to three design meetings to clarify what would happen to the wires, to the DC wires and what inverters we would use, how we were going connect the whole thing together."
>
> Wiring contractor (DEP01)

The wiring contractor (DEP) suggested the use of higher specification wiring to allow for smaller diameter wires, and although more expensive this allowed the accommodation of all the wires within the frame and bracketry already designed. The wiring contractor summarised the issue in the quote below - there is a hidden implication that this was just one of a number of issues that came up at the start of his involvement.

> We go back and say, look, here's our limited zone, can you get it all in here? Difficult, I'll tell you what, I'll change the wiring, I'll change the connector - I can do that then."
>
> Wiring contractor (DEP01)

The main contractor (WR), wiring contractor (DEP), façade contractor (QC), façade consultant (WH) and architect (MH) had a meeting to agree the wiring configuration and finalise bracket design. At this meeting the wiring contractor (DEP) suggested that the wiring be run vertically up the outside of the building and the inverters sited on the roof. The dynamics of the meeting are described in this extract from the interview with the main contractors.

> We had firmly gone with the route we had two rain-screen planks, we wanted it taken all the way back to the end walls and straight up. Which would actually reduce the visual impact because all you get is the horizontal I quite liked it, QC were happy with that, it made sense. There was a slightly difficult transition to the ends but that wasn't that difficult to resolve…DEP didn't want to do it that way. They wanted to just run straight up, in fact they wanted to run straight up literally on every row which was an absolute no, no. And then we took what they suggested and managed to group it between us. That was a joint thing, that was an architectural thing, a WR thing, they were quite good actually at listening to what was being said to them…Once we knew the wire ways that everybody was technically happy with then it was just finding the method to house them which was quite easy actually. "
>
> Main contractor (WR01)

As the meeting progressed, a design evolved which integrated a rear mounted riser behind the bracket which housed an almost invisible cable tray running vertically up the elevation. The risers were designed with a small cross-section (because of the smaller diameter wiring) and were to be painted the same colour as the brackets. The wiring contractor (DEP) realised that the PV louvres had been specified with the wrong type of connectors, but managed to find new connectors that satisfied regulations, and were smaller than the original ones. The wiring contractor outlined the issue below.

> They didn't have a connector. Well, they had a connector but it wasn't a connector that was going to work. There was MC3, as a connector which is fairly small, but it pushes together and there's no positive click to hold it together and you don't need a tool to disconnect it, and both those things are requirements nowadays…for safety reasons…So I specified a type of connector which is unusual, I've never seen one in this country before…which clicks together and is site assemble-able and is the diameter of a pen, it's quite a small thing. …Because space is all very tight.
>
> Wiring contractor (DEP01)

During the bracket and frame design the façade supplier (QC) thought about maintenance of the system and replacement of any broken louvres. The façade supplier designed a two part fixing mechanism so that the bracket could be removed after installation if access was needed. This design change necessitated slight reinforcement to the corners of the brackets and when the PV laminate supplier (LE) sent layout drawings of the panels to the façade supplier (QC) they found that the brackets and the PV connecters now interfered with each other. The PV laminate supplier (LE) was asked to move the PV connecters. To allow for access to cables within the brackets, the façade supplier (QC) designed a cableway and cover-plate system which clipped into place. The architect (MH) specified that the clips and cover-plates should be black to match the bracketry. The brackets had to be modified to allow for additional bolt connectors to be fitted which would push the Building Maintenance System (BMS) cleaning cradle away from the laminate panels when the laminate was being cleaned as part of maintenance (dirt reduces PV generation).

6.4.2 **Episode 3: technological frames**

In this episode the only technological frame not to be mobilised was the Generation Maximiser frame. Design hinged around the visible artefact of the PV louvre blade as the façade consultant (WH), façade supplier (QC), architect (MH) and PV laminate supplier (LE) adopted a more cooperative approach to the detail design and share a common frame of the Design Optimiser.

As the façade supplier (QC) and main contractor (WR) adopted the Cost Watcher frame, they wanted to change the way that the glass fitted into the frame, by bonding the frame rather than notching the glass. The resultant increase in thickness of the bracket caused friction, as the architect adopted the Design Aesthete frame and wanted the more streamline frame offered by the notched solution. The difference in views between the architect (MH) and the other actors are illustrated in the two following quotations - the architect was concerned with the robustness of the fixing and the aesthetics of the frame design, the façade supplier (QC) with the buildability and cost of the frame, and the main contractor (WR) with the cost.

> So this was tendered and the cladding package went to these guys, then they developed that design further and they've got rid of that [the notch]. They've essentially brought the bracket up to there and they've removed the notch in the glass - so it looks a lot more solid but aesthetically it's not as nice as what we had.
>
> Architect (MH01)

> The architect wanted just to have a little notch on the glass so that it would be held in by the framework so it couldn't, as he put it, slide out. And we said, we're not doing that because that added a significant amount to the cost of BIPVs and...[the façade supplier] said, no need to...they're bonded in here, they'll never fall out. So we said to [the architect], that's what happening, you're not having that, then it all went away but it was a little bit of a worry for a while because it added a substantial sum to our costs.
>
> Main contactor (WR02)

In this case there was no consensus and the main contractor imposed his decision to adopt the bonded solution.

The tension between Design Aesthete frame and the Cost Watcher frame occurred again as the issue of bowing of the glass was considered. The façade supplier (QC) proposed a cheaper “picture” frame (rather than the “razor blade” frame designed by the architect) to hold the glass in position. Although the main contractor (WR) could see the proposal through the Cost Watcher frame, he could also appreciate the implications in terms of the need to re-submit planning applications for the new design and therefore with the Time Sentry frame to the fore decided against the cheaper solution. The issue came to a head when the façade supplier (QC) asked for approval of the drawings for the frame extrusions and the resulting disagreement over the strength of the glass and the bowing of the louvres became difficult as the façade consultant (WH), PV laminate supplier (LE) and architect (MH) all mobilised the Risk Minimiser frame over concerns that they would be liable for any louvres which might deflect. The PV laminate supplier (LE) then mobilised the Time Sentry frame and took the decision to offer thicker glass at no extra cost. The following quotations show how the situation was understood by different project team members.

> I was worried that it’s a 2m piece of glass...I was worried it’s going to bow, [5mm laminate] sounded thin. It sounded really thin.
>
> Architect (MH01)

> Everybody said, oh it could sag, it could fall off the building, it could kill people. And I [said] well I don’t agree with any of you.... So we said we’d test it in our own factory….the glass never broke, never bent, never shattered, in fact we bent the bracket and a 12 millimetre stainless steel bolt, and the glass still did not crack or split ...QC are lovely to work with, they’re very good engineers, but they are cautious. QC said they wanted thicker glass and it’s QC’s choice because it’s a D and B contract”.
>
> Façade consultant (WH01)

> The original glass thickness specified was two layers of 5mm. On the other two buildings we’ve got two layers of 5mm on just brise-soleil and they sag in the middle. So more or less just on a whim we said, although we’re going to support on three sides, we’ll up the glass thickness to two layers of 6mm. But that wasn’t calculated.
>
> Main contractor (WR01)

> I think LE did it as a kind of almost a gesture - they're not bound by this impact load, because what they were saying is, the frame's adding an awful lot to the strength of our glass so we can't control that. But it's almost like they just said, look we'll give you another mil on each glass - you've got over the top now.
>
> Main contactor (WR02)

In both of the cases above, considerations of time dictated the solution. Another interesting point is that conflict can arise between actors sharing the same frame - in this case the façade supplier (QC), architect (MH) and PV laminate supplier (LE) shared the Risk Minimiser frame but could not agree on a solution until the PV laminate supplier (LE) broke the impasse. The resultant increased weight of the laminate and the need to increase the bracket sizes (and the subsequent bending of the brackets under their weight) was not anticipated by the façade supplier and architect and was of no concern to the PV laminate supplier (LE).

The architect (MH) adopted both the Design Aesthete and the User frame when he specified the white interlayer on the laminate to mask the rather "blocky" appearance of the PC cells within the laminate. When the PV laminate supplier (LE) reported a problem with the process and the appearance of irregular small spots on the interlayer, the architect (MH) viewed the problem through the Design Aesthete frame and asked for a printed screen layer instead - even though the spots would have been almost invisible to the users of the building.

As the project proceeded, the actors became more aware of the interconnection between the PV louvres, frames, wires and brackets. They adopted a Design Optimiser frame and this focussed them on more collaborative problem solving. This meant that the positions of connectors were defined, the cell layout was altered slightly to allow for the panels to locate properly in the frames, and the façade supplier (QC) was made aware that the frames needed to allow the PV wires within them to be curved slightly rather than crimped around sharp corners.

This collaborative approach extended into the decision of where the cables would enter the building and the architect (MH) was forced to abandon his objections to an external cable run (Design Aesthete) in the face of combined problem solving using the Design Optimiser frame. This focus on design optimisation allowed the team to accept the view of the architect (MH) for the wires to be concealed as much as possible and led to some innovative solutions for concealing wires within the frames and bracketry.

During this episode, actors mobilising the Design Optimiser frame were open to understanding the requirements of actors using other frames, and to a large extent accommodated them. The main contractor (WR) was concerned about the scaffolding schedule and how the wiring could be installed. The façade supplier (QC) designed a system of removable capping in the frames, brackets and cable-ways, to allow the wiring to be fitted by using the building maintenance system (BMS) cradle hoist after the façade was complete. He was also motivated to do this by adopting the Risk Minimiser frame so that the façade contract could be signed off as complete before the BIPV wiring was installed. It is noticeable that the willingness of actors adopting the Design Optimiser frame to collaborate in finding solutions masked the lack of a wiring contractor at this time. The late appointment of a wiring contractor meant that details of wiring thicknesses, bracket extrusion details and cable way dimensions could not be finalised. The situation was brought to a head when the architect (MH) adopted the Risk Minimiser frame and refused to sign off extrusion drawings for the façade supplier. The architect's refusal and the resulting delays made the main contractor see the project through the Time Sentry frame and he began to look for a wiring contractor with renewed vigour. Figure 6-3 shows how the network of actors, technological frames, problems and solutions played out during the detail design episode.

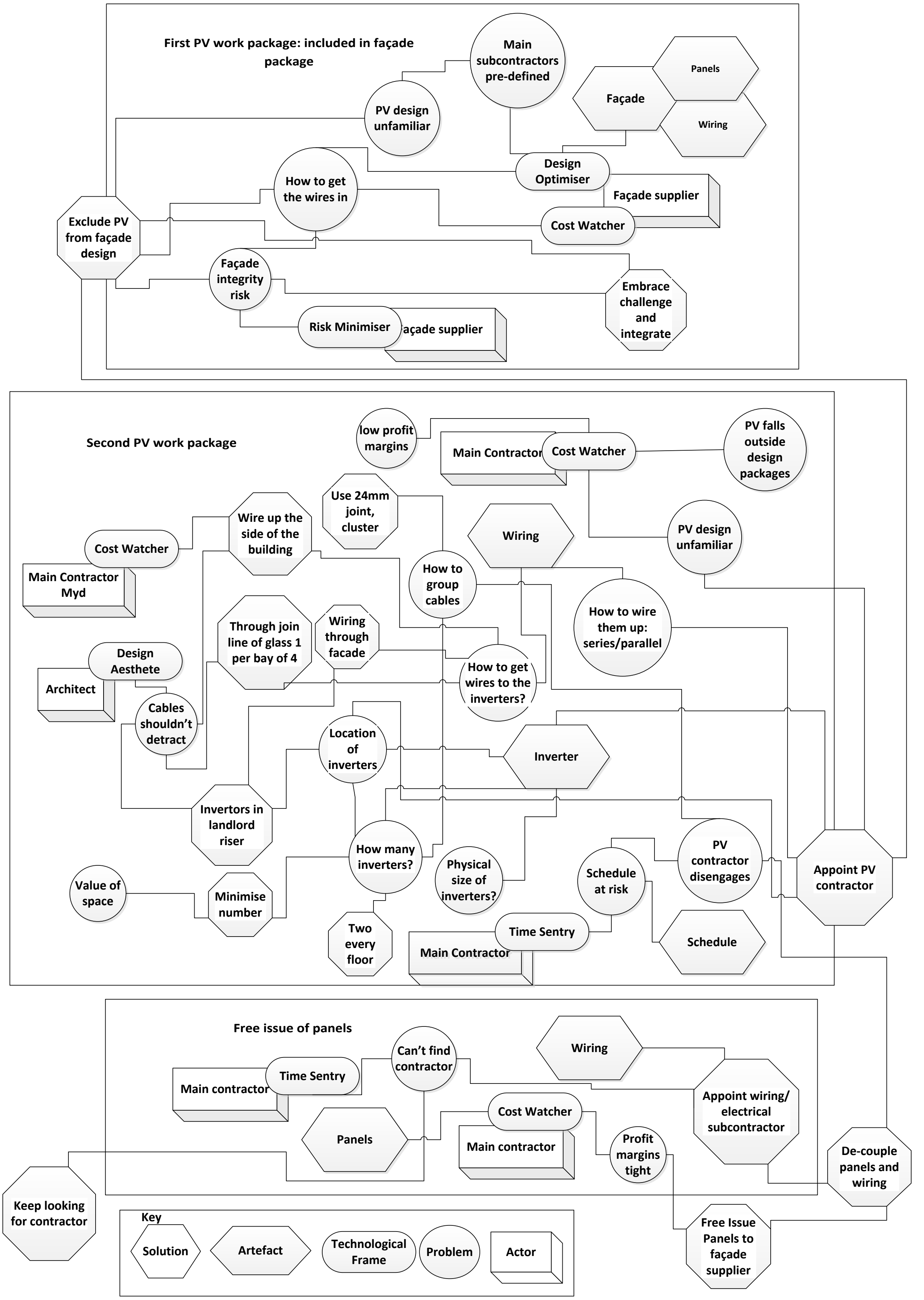


Figure 6-3: Technological frames mobilized in episode 3 (detail design), Vogue Terrace

In this episode the need to solve problems arising from the interdependence of artefacts dominated the problem solving, and the Design Optimiser frame dominated. The Risk Minimiser frame had a specific role to play in bringing problems to a head and forcing solutions. Tension between the actors also came from the presence of the schedule as a social artefact which represented and reinforced the Time Sentry frame.

6.4.3 Episode 3: co-development

Four instances of co-development occurred in this episode of the project.

i. The decision to bond rather than notch the PV louvres into the frames increased the size of the frames and altered their appearance.

ii. Increasing the thickness of the PV laminate glass led to changes in the design of the brackets and a re-positioning of PV cells within the laminate. The eventual deflection of the louvres impacted the appearance of the building.

iii. The interrelationship between the louvre brackets and frames and the BIPV system was particularly apparent in the episode. The BIPV wiring needed enough space within the frames and brackets to avoid crimping, the bolting system for the brackets interfered with the position of the PV connectors so these had to be moved, and the design of the extrusion sections for the brackets could not be finalised until the wiring contractor was appointed.

iv. Restrictions in terms of space available inside the frames and brackets meant that higher specification cables (smaller diameter) and different connectors had to be specified for the BIPV system.

6.5 Episode 4: wiring

This episode continues from the detail design of the frames and brackets and details how the wiring design was carried out.

6.5.1 Episode 4: narrative account

The use of higher specification cables and the choice of the vertical wiring route reduced the electrical losses in the system. The wiring contractor (DEP) calculated that rather than needing two inverters per floor the system would need just four larger inverters sited on the roof.

The main contractor (WR) and the façade supplier (QC) were happy that the wiring would run up to the roof level and penetrate the façade just at the parapet level through four smallish holes in the gasket, so negating concerns over water tightness. The main contractor (WR) was worried that the inverters - despite being waterproof - should be located undercover so that maintenance could be carried out in safety. He set about trying to find a suitable location on the roof space or failing that was content to build a small containment area on the roof. This issue had not been settled at the conclusion of this research. The following dialogue describes the dynamic nature of the decision-making process.

> Well they were going in the riser originally but then, because the wiring had to go up they were going to go on the roof. But I was never going to leave them on the roof, I always had an idea where I want to put them. I still haven't got them there yet, I’ve still got a bit of negotiation with the commercial people and find some space for them. I’ve found a space; I’ve just got to negotiate now.
>
> Main contractor (WR02)

> It’s a departure from the original concept idea.
>
> Main contractor (WR01)

The wiring contractor (DEP) had the responsibility to run cables as far as the inverter and G59 cabinet, but had had no contact with the main project wiring contractor in the design phase. This disconnect is summarised by the wiring contractor (DEP) and main contractor (WR), both of whom were expecting to have some issues over compatibility and duplicated work once installation started.

> So, we've got a cabinet which has got the G59 relay in it, and WR will wire to that and put in the metering. We might tell them what sort of meter to put in, but the incoming meter is nothing to do with us …we provide a generation meter, which will be in our G59 cabinet, and whether they want to monitor it or not is up to them. It'll have a modbus output, so they can connect it into their building.
>
> , Wiring contractor (DEP01)

> But again that sort of thing had to be packaged up and worked out who was doing what. But [the main electrical contractor] left us an inverter to do that, but at that isolator, the electrical consumption sort of responsibility has ended…but there wasn't a consultant responsible, sort of thing, but fortunately we've got DEP.
>
> Main contractor (WR02)

6.5.2 Episode 4: technological frames

The wiring contractor (DEP) adopted the Design Optimiser frame to work through the problems facing him when he came on board the project. His suggestions of: higher specification wires; smaller connectors; four inverters to be sited on the roof; and a new way of running the wires up the building instead of across, all took account of the constraints on other actors in terms of limited space inside the brackets and frames, and aesthetic concerns over external cabling. For the first time the main contractor (WR) was seen to view the technology through the User frame and insisted that the cabinets be housed inside the roof's plant room so that maintenance could be carried out safely. This is illustrated by the extract below.

> They are going, yeah, they're weatherproof, but they are going inside, I don't like the idea of having people to work on them if they ever do, outside.
>
> Main contractor (WR02)

This again illustrates the power of the Design Optimiser frame to enable collaborative problem solving. Figure 6-4 summarises the changing pattern of problems and solutions as the wiring design progressed and shows how the technological frames were mobilised by the actors.

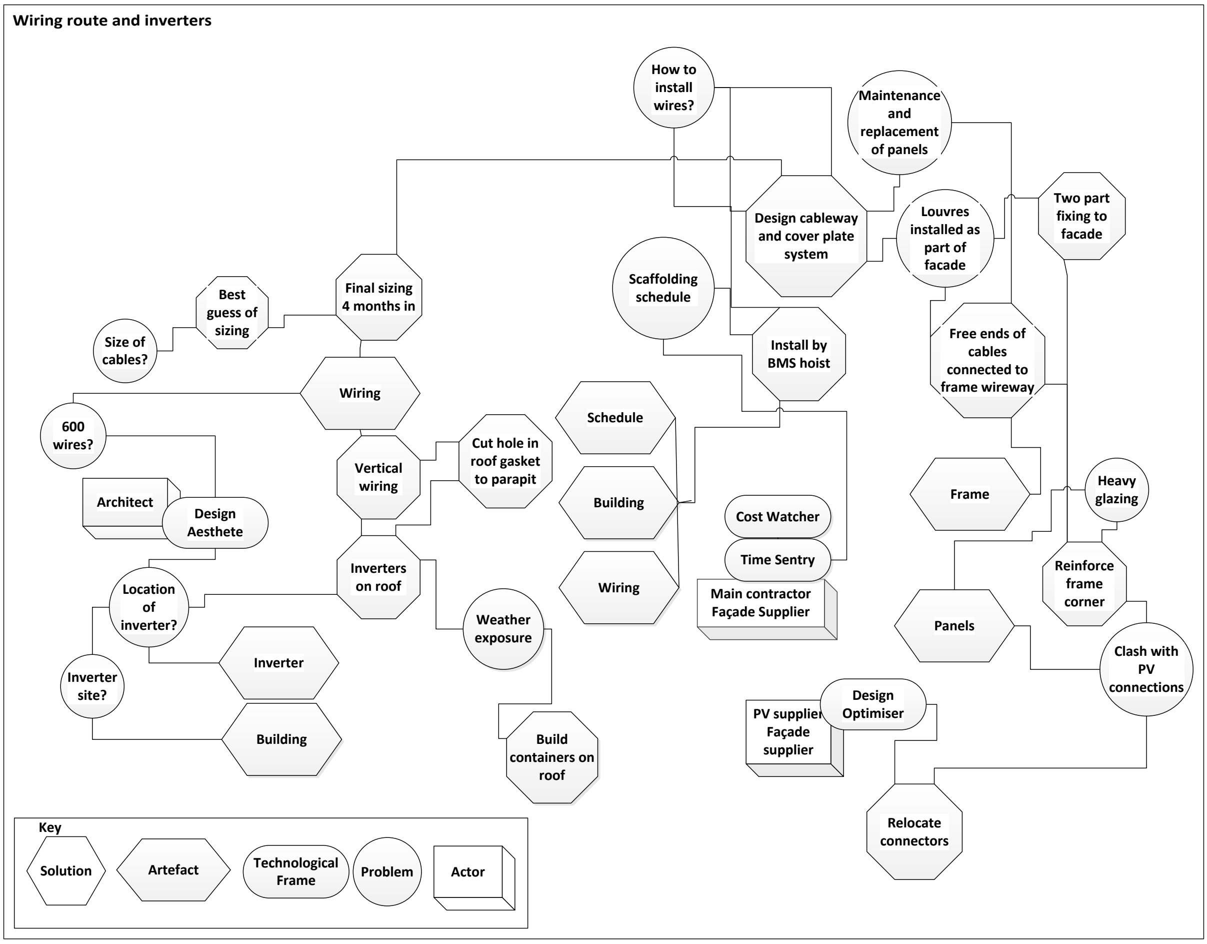


Figure 6-4: Technological frames mobilized in episode 4 (wiring), Vogue Terrace

6.5.3 Episode 4: co-development

One clear example of co-development of the building and the BIPV system occurred during this episode of the project. It undoubtedly affected the appearance of the building and led to improvements in the efficiency of the BIPV system.

The number of inverters was reduced to four and could be easily accommodated at roof level. This led to a redesign of the bracketry system to allow for the wires to be run vertically up the building within an innovative containment and capping system. This rerouting of the wiring meant that the visibility of the external wiring runs was very much reduced.

6.6 Episode 5: installation

This episode continues from the detail design of the wiring of the BIPV and deals with the installation of the BIPV system.

6.6.1 Episode 5: narrative account

As there was a separation between the façade contract and the electrical contract, the two systems were installed separately. The façade (including the PV brise-soleil), was to be installed first and then the wiring system put in place. The scaffolding around the south elevation had to be dismantled just after the façade had been installed and this meant that the electrical installation work had to be done without scaffolding.

The contract specified that each PV panel be tested for generation before being installed, using a simple voltage test. On site, each brise-soleil panel was removed from its stillage and tested to prove a current was being generated. After that the façade supplier’s (QC) fitters bolted the louvre assembly to the window and the whole assembly was hoisted into place on the façade using a crane. Once all the façade had been installed the PV wiring installation was carried out using the building maintenance system (BMS) cradle. This required the PV wiring contractor (DEP) to remove the clips from the brackets and cableway, fit connectors to the trailing ends of wire from the PV panels, connect the wiring to the connectors, and feed the wiring into the cableway and replace the clips. The BMS cradle was used to gain access to the louvres, two at a time. Once this was done, the wiring was taken to the top of the building via the cable ways, laid through the slot in the parapet gasket, and taken to the inverters. This process had not been started by the time the research finished.

Once the façade was erected the architect (MH) noticed that the brise-soleil brackets were deflecting and asked for this to be corrected. The façade supplier (QC) had to replace the two-part pin assembly holding the brackets with thicker pins and reflected that this was probably due to the increased weight from the thicker laminate panels.

6.6.2 **Episode 5: technological frames**

During this episode the collaborative problem solving was less in evidence and the actors worked in silos, mobilising the Risk Minimiser frame to ensure that their parts of the contract were completed.

Figure 6-5 summarises the changing pattern of problems and solutions as the installation progressed.

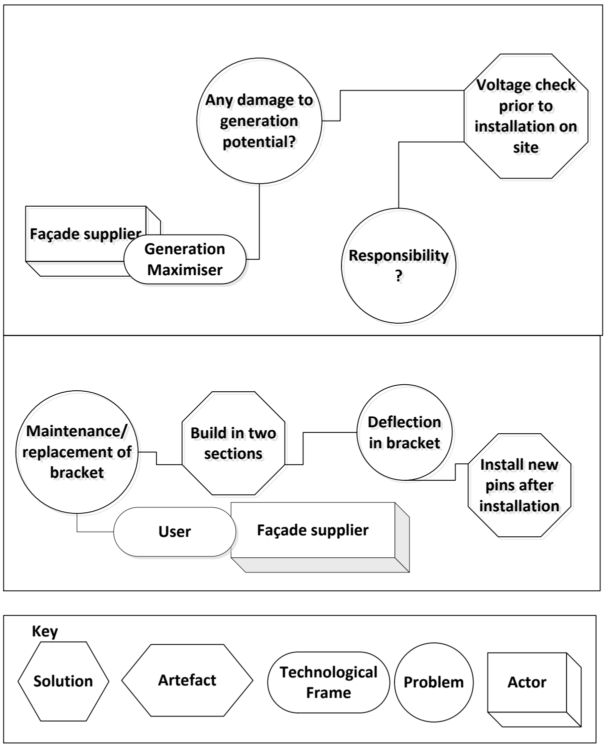


Figure 6-5: Technological frames mobilized in episode 5 (installation), Vogue Terrace

6.6.3 Episode 5: co-development

The scaffolding schedule and the separation of façade and wiring packages meant that the installation of the two systems occurred in series - the electrical work being carried out using the BMS hoist once the façade had been completed.

6.7 Summary

This final section of the chapter brings together the five episodes to examine the case as a whole, exploring the technological frames and RSG’s, the co-development of the BIPV and the building as the project proceeded, and the issues and challenges which were particular to this project.

6.7.1 Technological frames

The analysis for each project episode has illustrated how the technological frames were mobilised by the actors in the project and has explored how tensions played out between the actors mobilising different technological frames as they found solutions to problems. This section summarises the pattern of technological frames used and investigates the way that actors mobilised different frames at different times throughout the project.

As this analysis suggests, RSGs are composed of project actors who share a view of the technology rather than those who occupy common positions or roles. For example, the two main contractors (WR01 and WR02) adopted different frames over the issue of wiring runs. The design manager (WR01) was more concerned with aesthetics (Design Aesthete) with the M&E manager (WR02) being concerned about design efficiency (Design Optimiser).

While most actors clearly identified with a particular frame, they also accepted the views of actors who saw the technology through other frames. In some cases this, together with an unfolding network of problems and solutions, allowed them to move or shift between frames. For example, during the initial design phase the architect (MH) was concerned with the aesthetics of the building, but was also interested in establishing building's green credentials. Later, during talks with the PV laminate supplier (LE), the architect (MH) became more invested in the energy generation of the panels. The client at the start shared the architect's concern with green credentials and aesthetic concerns, but as the project advanced the client began to think about the users and their concern to minimise disruptions during maintenance of the inverters.

The analysis clearly shows that project actors do not stay frozen in one frame, but switch around as the project progresses. The pattern of shifting frames can partially be ascribed to changes in actors' responsibilities and interests as the project progressed. In this case study the pre-contract project manager (WR) initially supported BIPV as part of the total sustainable design of the building, and designed panels accordingly. As the project entered the construction stage and the pre-contract project manager took on the role of the main project contractor (WR), cost became an issue. In his new role and new context, the main contractor suggested replacing the BIPV panels with conventional glass. The proposal to remove the BIPV panels from the façade would have met cost reduction targets, but would have totally missed the Green Guardian's desire to generate green electricity, and would have failed to satisfy planning conditions. From the perspective of SCOT, this shift can be analysed as a movement from one RSG to another. This example suggests that the reconfiguration of RSGs often occurs as the contractual relations between client, main contractor and suppliers change and that these shifts can affect problem resolution.

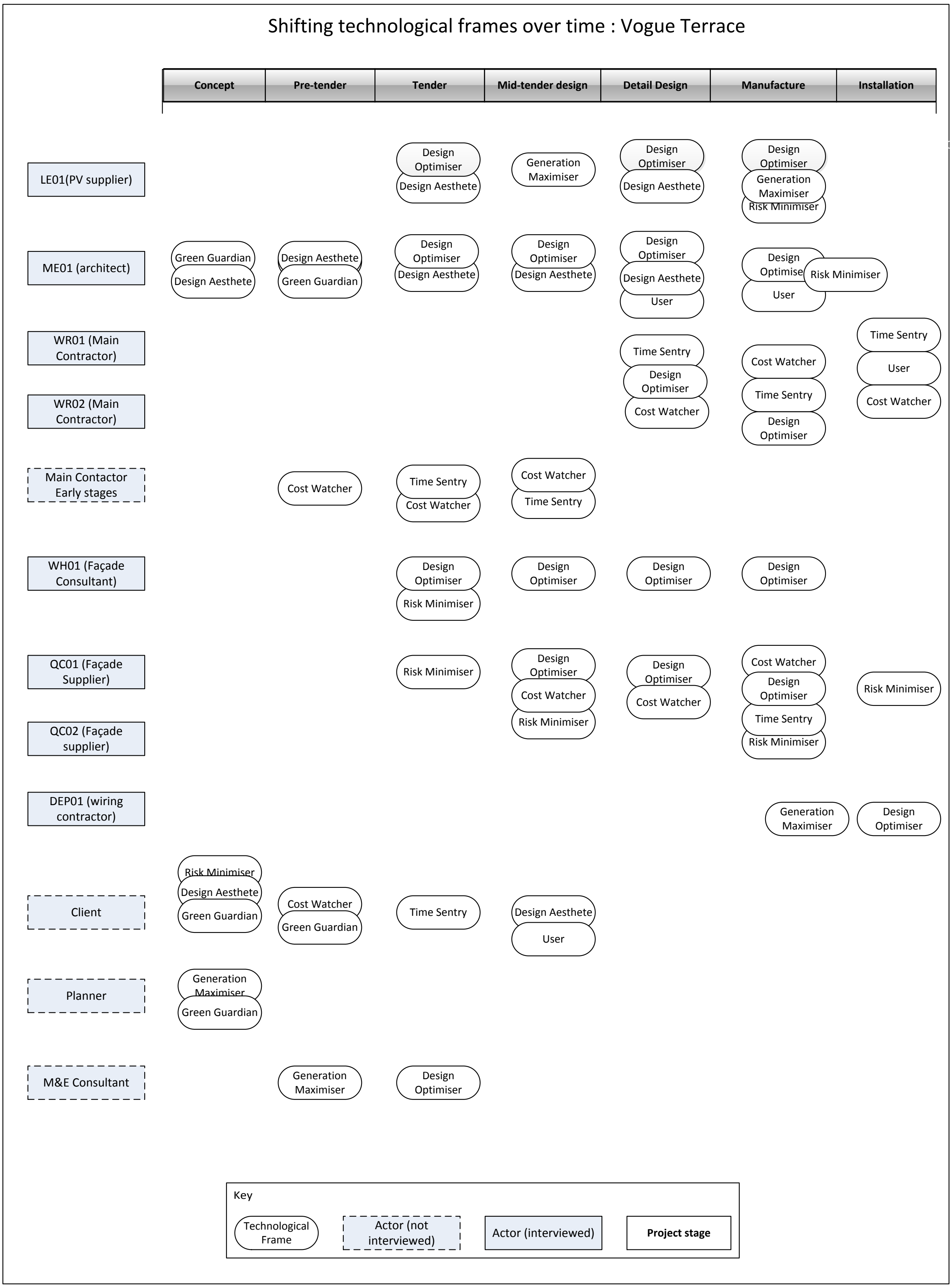
A number of elements contributed to this seeming movement between technological frames: different project actors coming to understand the other actors' perspectives; changing responsibilities of actors; changing contractual relations between actors; shifting problems around which views are formulated; and changes in design of BIPV and the building as certain features get stabilized. What is clear is that it is this shifting of frames seemed to encourage the resolution of problems and allowed acceptable solutions to be developed.

Membership of a technological frame is not exclusive - one actor can be a member of more than one RSG at any one time, and loyalty to the group is very transient. In the initial design phase the actors involved had two different requirements for the technology - it should be part of a cohesive plan for the three buildings and it should satisfy renewable energy planning requirements. The actors involved were the project manager (WR), client, architect (MH) and planning officer; the latter mainly had an interest in the renewable energy targets, but the architect and client also shared a desire for an aesthetically pleasing, forward looking building, whilst the project manager (WR) was also interested in the buildability of the project. For example, as the architect (MH) was novated to the main contractor (WR), the dominant focus frame switched from Green Guardian to Design Optimiser. The PV laminate supplier (LE) was concerned with Maximising Generation at the tender stage, then shifted to the Design Optimiser frame during detail design and then switched back to the Generation Maximiser frame as he became responsible for testing the output from the panels. It is interesting to note that the weight that an actor ascribed to a technological frame bore a relationship to the stages of the project at which key contractual points are reached. This point is illustrated in Figure 6-6 which shows how the actors mobilised different technological frames as the project proceeded.

Three key observations about the role of certain technological frames indicate a link to mechanisms of problem solving. First, the frame of Generation Maximiser appeared very rarely and in general it was the PV laminate supplier (LE) who used the Generation Maximiser frame, even though his contract had no generation figures attached to it. This might be considered surprising given the initially assumed primary function of BIPV to produce electricity, and points to a need to explore further the reasons or motivations for the original specification of BIPV on the project and its apparent influence on the development of the system. Secondly, the Time Sentry and Risk Minimiser frames had a disproportionally high effect on problem solving, with the effects not always visible to the whole team. For example, the pressure of meeting the tender package deadlines and concerns over risk led the façade supplier (QC) to decide not to include PV within the package. This decision shaped the future development of the BIPV and the building, but the reasons behind the decision were not visible to the other project actors. Thirdly, the Design Optimiser frame had an inherent quality which promoted a more collaborative problem solving mechanism, which allowed integrated decision-making around both the building and the BIPV system.

When mapped onto the conventional project stages (Figure 6-6), it is apparent that some shifts in the dominance of a technological frame occurred at transition points, where the project changed from design to installation, or from concept to pre-tender design. The composition of Design Optimiser, Risk Minimiser and Time Sentry frames in particular were very fluid, with nearly every actor mobilising these over the course of the project, but at different times. The dominance of an RSG appeared to vary over the course of the project but approximated to the stage of the project (for example, the Design Optimiser frame dominated during the detail design stage etc.). The façade supplier (QC) adopted the Design Optimiser frame during the design stage, but switched to the Time Watcher frame as the installation phase approached. The client first adopted the Green Guardian frame when defining his requirements for the building, but once the tenders were approved adopted more of the Time Sentry frame. The Risk Minimiser frame appeared at contract transition points in the project - the façade supplier (QC) viewed the tender document through the Risk Minimiser frame and decided to reject the idea of including the BIPV work package. Similarly, the architect adopted the Risk Minimiser frame once he was novated to the main contractor and was asked to sign off drawings. It is notable that in this project the Risk Minimiser frame closed down innovation opportunities rather than encourage them. Chapter 9 will explore these factors further by comparing the different case studies.

Figure 6-6 lists the project actors and shows how the frames that they mobilised shifted over the course of the project.



Shifting technological frames over time : Vogue Terrace

	Concept	Pre-tender	Tender	Mid-tender design	Detail Design	Manufacture	Installation
LE01(PV supplier)			Design Optimiser Design Aesthete	Generation Maximiser	Design Optimiser Design Aesthete	Design Optimiser Generation Maximiser Risk Minimiser	
ME01 (architect)	Green Guardian Design Aesthete	Design Aesthete Green Guardian	Design Optimiser Design Aesthete	Design Optimiser Design Aesthete	Design Optimiser Design Aesthete User	Design Optimiser Risk Minimiser User	
WR01 (Main Contractor) WR02 (Main Contractor)					Time Sentry Design Optimiser Cost Watcher	Cost Watcher Time Sentry Design Optimiser	Time Sentry User Cost Watcher
Main Contactor Early stages		Cost Watcher	Time Sentry Cost Watcher	Cost Watcher Time Sentry			
WH01 (Façade Consultant)			Design Optimiser Risk Minimiser	Design Optimiser	Design Optimiser	Design Optimiser	
QC01 (Façade Supplier) QC02 (Façade supplier)			Risk Minimiser	Design Optimiser Cost Watcher Risk Minimiser	Design Optimiser Cost Watcher	Cost Watcher Design Optimiser Time Sentry Risk Minimiser	Risk Minimiser
DEP01 (wiring contractor)						Generation Maximiser	Design Optimiser
Client	Risk Minimiser Design Aesthete Green Guardian	Cost Watcher Green Guardian	Time Sentry	Design Aesthete User			
Planner	Generation Maximiser Green Guardian						
M&E Consultant		Generation Maximiser	Design Optimiser				

Key

Technological Frame

Actor (not interviewed)

Actor (interviewed)

Project stage

Figure 6-6: Movement of actors between technological frames as project proceeds

6.7.2 The co-development of the BIPV and the building

The discussion of the five episodes of this project signalled a number of key moments of co-development; the discussion which follows explores the co-development story of the building and the technology in greater detail and shows how this mutual articulation occurred. Three types of co-development of the BIPV system and the building were identified during the analysis: lock-in, interdependence of appearance, and mutual adjustment and adaptation. These are discussed in greater detail in the following section. In addition to the analysis of co-development, examples of unfolding innovation are highlighted as the BIPV system was integrated within the building.

Figure 6-7 illustrates the co-development story by showing the interconnectivity between the elements of the building and BIPV. 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. The diagrams below were derived from a SCOT analytical framework, 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 are used to illustrate specific points in the discussion which follows. 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.

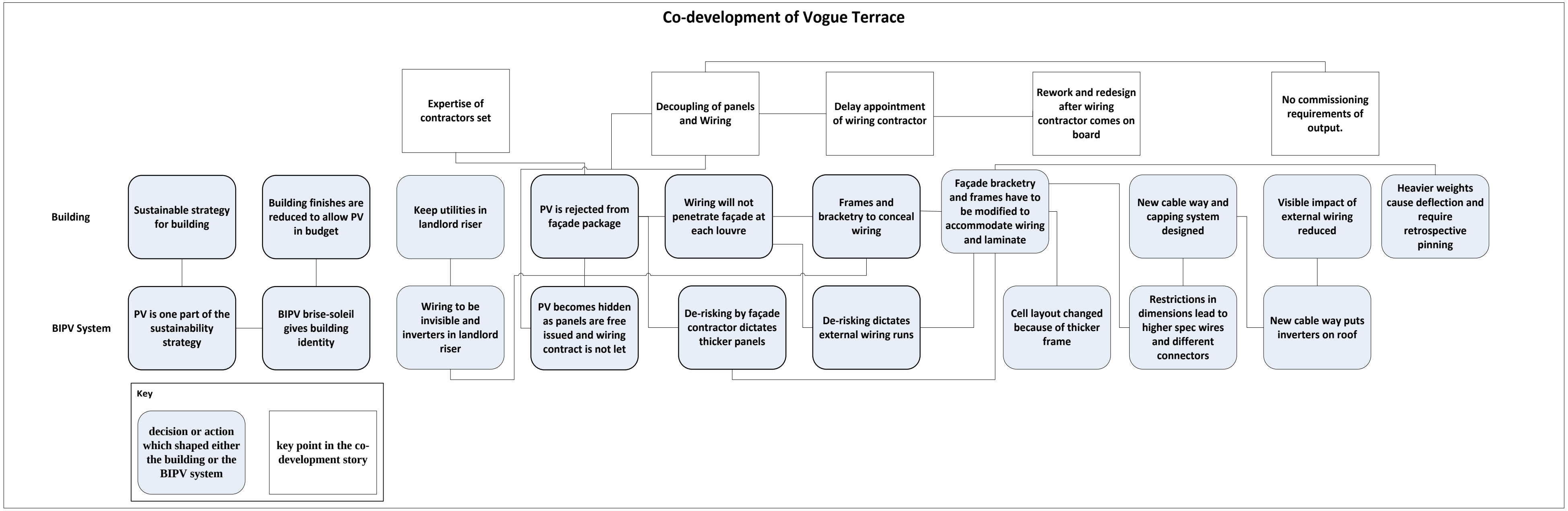


Figure 6-7: Co-development diagram Vogue Terrace

Lock in

Lock-in (in terms of the co-development of the building and the BIPV system) occurred when a decision or series of decisions pushed the design into a direction from which there was no turning back. Two examples of this type of co-development occurred in this project

Firstly in the initial stages of the design, when the client elected to use BIPV as part of the building identity and as a result chose to reduce the finish quality in the building rather than replace the BIPV system with a roof mounted system. Figure 6-8 shows this interdependence.

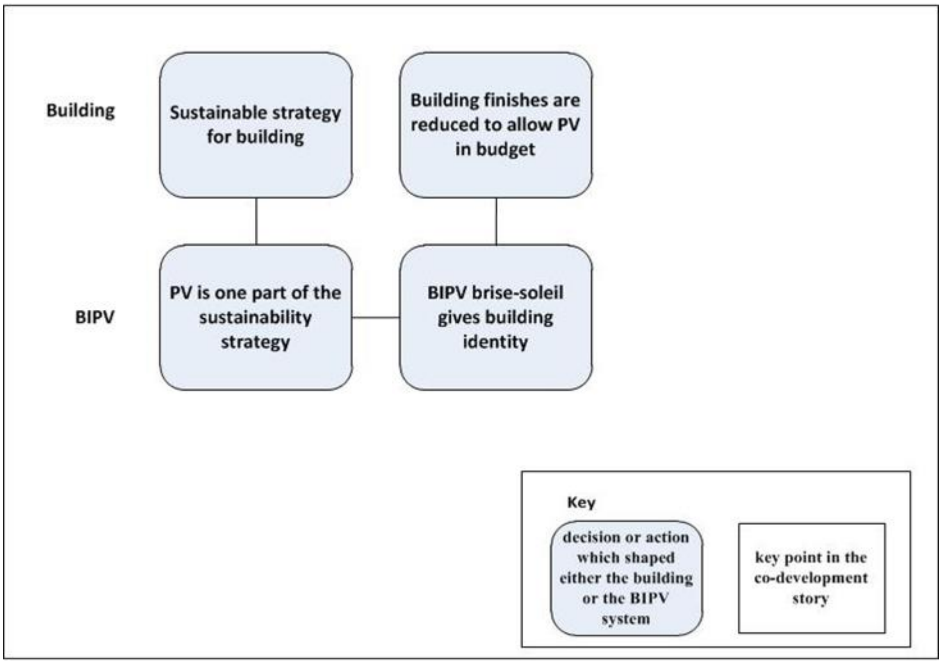


Figure 6-8: Co-development - lock-in part 1

Second, the decision to use the same supply chain as used in the previous phases of the development set in train the procurement decisions which separated the BIPV system from the building and decoupled the BIPV panels from the electrical BIPV system. The client tried to ensure project efficiency by specifying that the same major contractors be used in this project. This resulted in the façade supplier (who had no previous expertise in BIPV) rejecting the BIPV system from his work package. As a result, the main contractor tried to find a BIPV system supplier, but when this failed, decided to decouple the BIPV system - both from the building and from itself. Thus the BIPV system was broken down into the laminated panels and the electrical system. From then on the BIPV system as a whole became invisible to the project team and instead became two artefacts - the louvres and the miscellany of wiring. The second part of lock-in in this example is when the façade supplier refused to allow the wires from the BIPV system to penetrate the façade at the locations of the louvres and insisted that the wires be run externally to collection points where they could penetrate the façade in smaller, controlled ways. This led to a complicated interrelationship between the frames, brackets and wiring and also meant that the wires were visible on the external face of the building. Finally, the de-coupling of the BIPV system meant that no-one was responsible for delivering a particular electrical output from the building and so commissioning was just an "on-off" exercise. Figure 6-9 illustrates this co-development mechanism.

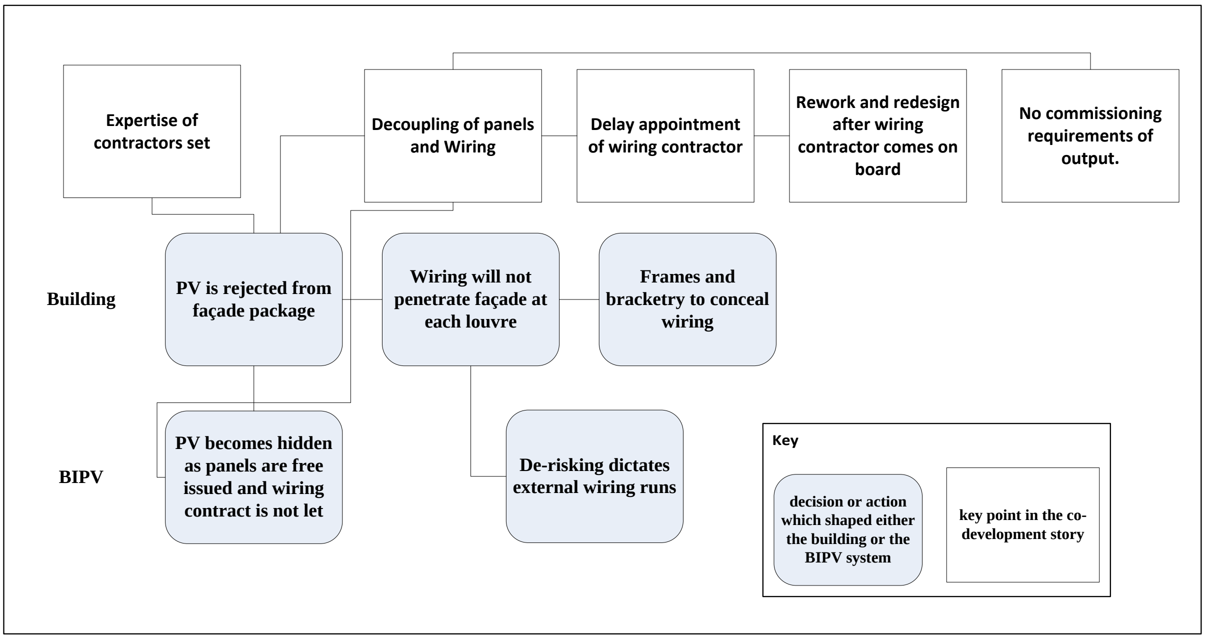


Figure 6-9: Co-development - lock-in part 2

Homogeneity of appearance

The second series of co-development events relates to homogeneity of appearance of the BIPV and the building. This is where the BIPV system directly affects the appearance of the building in some way and vice-versa. This type of co-development is not necessarily on a very large scale, but occurs at an externally visible level. The first and most obvious example of this co-development is with the initial specification of BIPV brise-soleil louvres on the south elevation of the building. The design of the frame to hold the laminated PV panels determined the shape and look of all the louvres on the elevation - not just the PV ones. A second example of this type of co-development is when the BIPV wires ran on the outside of the façade and so changed the flat appearance of the façade to one which had cableways running vertically up the building. The project team in the end managed to design the cable-ways to look as though they were part of the window bracketry, but the façade looked different from the architect’s intention. The final example of this interdependence of appearance is the effect of the thicker glass laminated PV panels on the frame and bracketry sizing and the resulting deflection of the louvres which affected the appearance of the building - both because the bracketry and frame design were chunkier than before, but also because the louvres were not straight on the façade because of the deflection. Figure 6-10 illustrates these interrelationships.

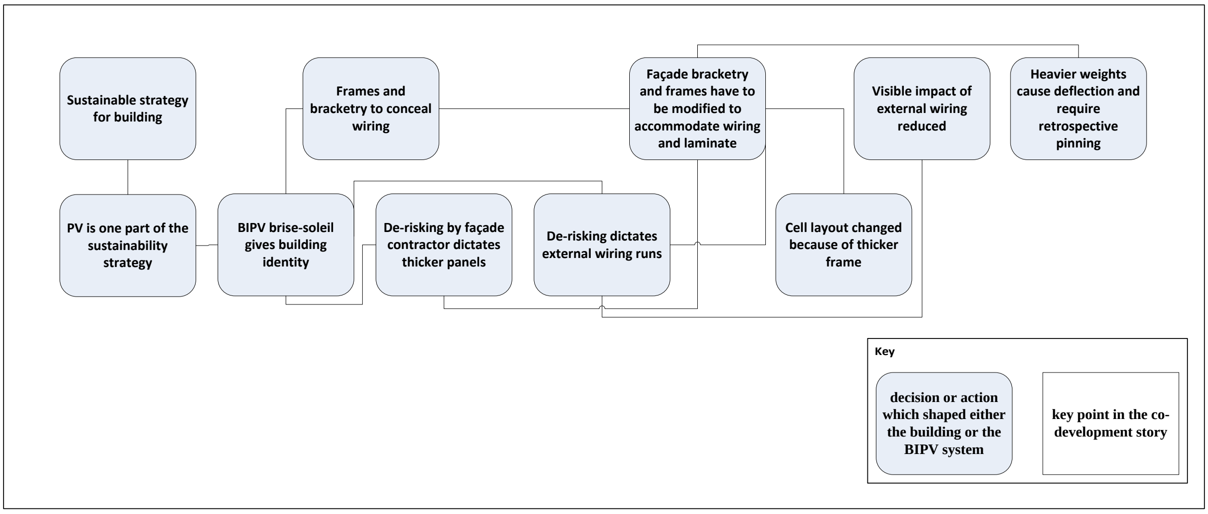


Figure 6-10: Co-development - homogeneity of appearance

The mutual adjustments of the building and BIPV

The mutual adjustment of building shape and BIPV design occurred when the often small scale adjustments were made to accommodate the BIPV system and the building to each other. The best illustration of this is the mutual development of the frames and bracketry. At the start of the project, these artefacts were not thought of as part of the BIPV system - rather as part of the façade work package. Indeed the façade supplier had been very keen to separate the façade design from the BIPV system. As the project progressed, the decision not to allow individual wires to penetrated the frames or façade meant that the frames and brackets became the carriers of the wires and so had to be designed to accommodate them. Considerations over providing enough room within the frames to prevent the wires being crimped, shifting the position of the BIPV connectors to allow for bracket corners, and changing the PV cell layout to accommodate larger frames, are all examples of these mutual adjustments. Figure 6-11 illustrates this process.

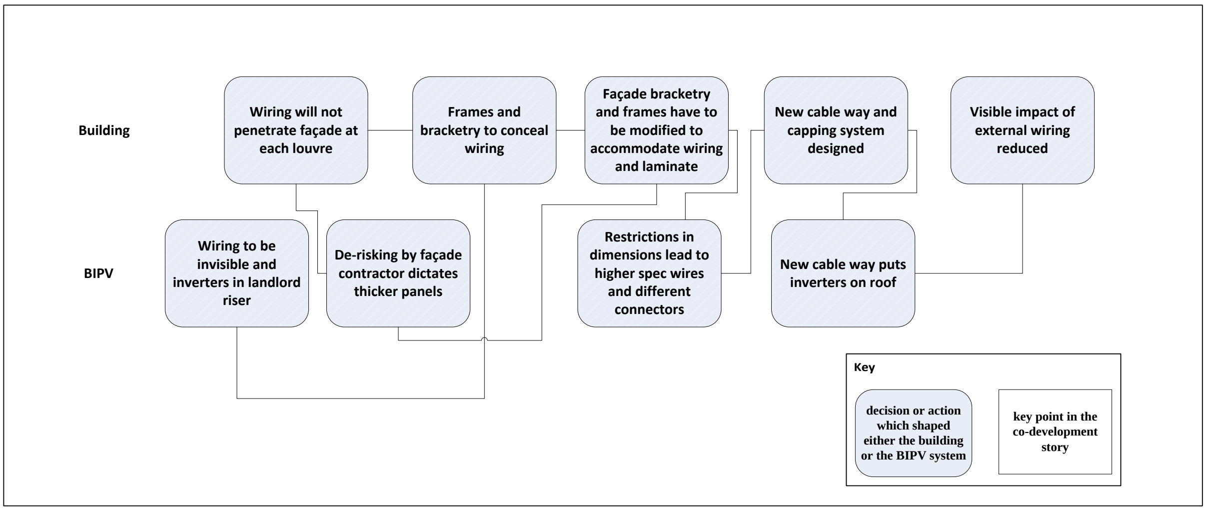


Figure 6-11: Co-development - mutual adjustment

It is interesting to note that the process of mutual adjustment gave rise both to the innovative cableway and capping system and to the inclusion of thinner, higher specification cables which not only reduced the number of inverters, but also improved the system efficiency by minimising power loss through the wires. This shows that unfolding innovation is part of the process of adoption of BIPV within a project.

In summary, Vogue Terrace illustrates three types of co-development: lock-in; homogeneity of appearance; and mutual adjustment and adaptation. The case study also has examples of unfolding innovation as the BIPV was integrated within the building. These mechanisms and their importance on the adoption of innovation are discussed in the Chapter 9.

6.8 Issues about BIPV and the challenges which it poses for project teams

As part of this analysis, there were several issues which have particular relevance for project teams. The architect, M&E consultant (DC), façade supplier (QC) and main contractor (WR) were relatively unfamiliar with BIPV and this led to several decisions which had profound implications on the subsequent direction of the project. The lack of familiarity of the façade supplier with BIPV led to a decoupling of BIPV panels and the rest of the technical system associated with BIPV. The main contractor was not aware of the interdependence of the two aspects of design and so used standard ways of dividing work packages to allocate BIPV work. This led to late decision-making over wiring runs and disconnected decisions about brackets and frames, glass sizing and inverter location.

The main contractor was unfamiliar with the electrical requirements of the BIPV system and assumed that the main electrical contractor was the expert. As the following extract shows, this was not the case and the main contractor ended up having to develop the electrical specification as the project continued.

> He is one person who we thought might have had more input, the electrical consultant hasn't picked up everything he needs to…It's just that because these weren't part of his specification, he's just left the connection for them, that's it. So we've virtually written the [BIPV electrical] spec our self.
>
> Main contractor (WR02)

The unfamiliarity also led to the façade supplier rejecting involvement with the new technology and the eventual de-coupling of the BIPV system.

During the project there was no single source of expertise for the BIPV system. The PV laminate supplier advised about panel layouts, but did not get involved with the wiring or configuration for strings. The façade supplier assumed that the PV laminate supplier supplied the system and the main contractor relied on the electrical contractor to understand the G59 connections. The architect and main contractor did not have a single "go-to" expert and relied on gaining knowledge from suppliers of different parts of the system at different times, leading to a fragmented approach and disconnected design. The following small quotation illustrates the belief that there is one person who will answer the questions, but the "he" in this extract does not exist! It was only at the end of the project that the BIPV wiring contractor became the “expert”, but his expertise was in fact with only part of the BIPV - he had no knowledge about the PV panels and their design or output.

> But we think he’s going to come back and say I need two every floor, where, where can they go?
>
> Architect (MH01)

The visible part of BIPV dominated the design and the lack of understanding that the technology is a system led to ad-hoc decisions being taken, with little to no appreciation of the knock-on effect of these decisions. An example is the re-sizing of the PV louvre thickness which led to thicker frames and eventual deflection of the holding pins. The lack of understanding that the 672 panels would need over 600 wires to be accommodated meant that in the end the wiring was fixed on the outside of the building rather than being truly integrated. The façade supplier was adamant that the inverters were nothing to do with his system, although the location of the inverters dictated where the cables were to run and how they were to be contained within his frames and bracketry.

One other issue arising from the analysis which has implications for the inclusion of BIPV in projects is the effect which the motive for adopting the technology had on design decisions. For example, the desire to use BIPV as a statement of modernity led to greater importance being given to the aesthetics of the design rather than the generation potential of the technology. This distinction between the visual characteristics of the system and its function of electricity generation led to decisions being taken which made the integration of the system more problematic and certainly had an impact on the overall efficiency of the generation system.

An observation about project teams is the effect of artefacts such as the project schedule. These artefacts are not present in a material form and are constructed as part of the project management process, rather than being part of the technology or the building. They will be referred to as social artefacts in the discussion which follow. Social artefacts at times dominated the decision-making, and appear to have huge effects on the stabilisation and closure of problems and solutions.

Standard construction processes and practices also had a large effect on the integration of BIPV on the project. Three main issues of contracts, the effect of continuity and collaboration of the project teams appear to be particularly important. Firstly, in construction projects, the way that contracts are placed is usually part of a critical path which establishes the order in which contracts should be let. With a new technology there are new dependencies which are not obvious and this can lead to tensions. Second, lack of continuity in personnel over key project stages led to misunderstandings and losses of information. Third, collaboration is often a very valued commodity in construction, but in this project using the previous project team locked-in unfamiliarity in the area of BIPV and also locked-in a collaborative element to the relationships. This possibly led to the main contractor acquiescing to the façade supplier’s refusal to include BIPV in the tender. Similarly, the fact that the new BIPV supplier was a subsidiary of the main contractor led to a very relaxed relationship. The past collaboration between the façade supplier and main contractor appears to have made the decision to free issue the PV panels a very simple one, but with a more formal relationship it might have been inspected more closely before agreement was reached. The façade supplier agreed to have the PV panels free issued in order and understood that this would allow the main contractor to make more of a profit margin. Finally, the long time span of the project and the fast changing nature of parts of the technology allowed technology to catch up with inconsistencies in the design. So newer, more efficient wiring specifications allowed for reduced extrusion sizing to accommodate the wires and more developments in inverters paved the way for roof mounted inverters.

These challenges for construction practices are discussed in more detail in Chapter 9.

Chapter 7: Case Study - Future Green

This chapter presents the second case study (Future Green), with a general description of the project, followed by the case study being broken down into five separate episodes: initial scheme; pre-tender design; tender process; detail design; and installation.. For each episode a narrative account of what happened focuses on the succession of problems encountered and solutions developed, reflecting on the changing technological frames of the actors and exploring the co-development of the building and the BIPV. The chapter then summarises the way that actors mobilised different frames at different times throughout the project and explores the mechanisms of co-development, between the building and the technology.

7.1 Description

Future Green is a commercial science hub which was the first building to be erected on a 24-acre site in a large science park development. The project was a joint partnership between a University, City Council and several other strategic partners. Future Green is a seven-floor mixed space, with the ground floor being an exhibition hub and with office accommodation on the upper floors. The University occupies the entire second floor and has moved some of its continuing professional development (CPD) facilities into the building. The clients renting the offices are expected to be start-up businesses within the field of sustainability. Although predominantly owned and run by the Council, the building is operated by a private company which is responsible for letting space and running building on a day-to-day basis.

The project was promoted by the client as a flagship for sustainability and BIPV was used to demonstrate this commitment. BIPV panels are incorporated into ten of the twelve windows on the south-west elevation of the building and other sustainable features include a small solar thermal installation on the roof of the building, a green wall on the west elevation and natural ventilation on the upper floors. The building features many irregularly spaced, tall, narrow windows, which make a bold architectural statement against gold cladding and green vertical brise-soleil panels. The project used a Design and Build contract. The City Council had a significant say in defining the functional use of the building, but the University was more influential in the early design stages, particularly regarding the building envelope and the technologies employed.

Design for the project started in 2010 and the construction of Future Green began in late 2013. The installation of BIPV was completed by August 2014 and the project was completed by November 2014. Twelve interviews with members of the project team were conducted over a one and a half year period. The first was conducted just as installation of the PV windows had taken place and the last just after handover of the building to the client. Chapter 5 (Methods) gives detailed information about those interviewed. In the following analysis interviewees are referenced by the firm they represent: letting manager (FS); architect (NW); main contractor (TH); M&E design consultant (SAW); façade supplier (RR); glazing supplier (WA); M&E contractor (BSW); and PV laminate supplier (LE). The PV laminate supplier (LE) supplied PV laminate panels to the glazing contractor (WA). A number is added to the reference as a unique identifier for each actor in the firm (for example: “main contractor (TH01)” represents the main contractor firm - TH, and is the first actor interviewed from that firm. “Main contractor (TH02)” indicates the second person interviewed at the main contractor firm).

7.2 Episode 1: the initial Scheme

The first episode covers the development of the concept design for the building to the point at which the initial design for both the outline shape of the building and the configuration of the BIPV system had been defined.

7.2.1 Episode 1: narrative account

The clients (City Council and the University) commissioned the building as the first stage of a mixed development of science hub, commercial offices, retail outlets and residential housing. They were keen to attract European Regional Development Funding (ERDF)[1] for the project and therefore had to demonstrate at least BREEAM Very Good and preferably BREEAM Excellent rating. This necessitated achieving an Energy Performance Certificate (EPC) rating of at least "B" and preferably "A".

Initial discussions about the layout and requirements of the building were held between the client, the letting manager (FS), M&E design consultant (SAW) and architect (NW). During these meetings, the client was concerned with obtaining EU funding and was keen to use renewable energy to promote and sell the building to start-up companies interested in sustainability. The letting manager (FS) was keen to have a flexible space on the ground floor, with lettable offices above. The architect wanted the building to make a statement and for the sustainable element to be part of the fabric of the building. The M&E design consultant (SAW) and architect (NW) developed ideas for the sustainable element of the project and these included the inclusion of a biomass boiler, the use of a geothermal heating system, the use of heat recovery fins, various schemes for a green roof and walls, and the use

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[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/9455/National_ERDF_handbook.pdf

of solar energy (both solar thermal and PV). At this stage the architect (NW) and M&E design consultant (SAW) were more concerned with establishing the green credentials of the building rather than with costs, detail schemes or time frames.

The client, architect (NW) and M&E design consultant (SAW) held a review of the sustainability options with a view to selecting which technologies to use. The M&E design consultant (SAW) identified his role to present the options and help the client to make an informed choice both in terms of cost and of meeting BREEAM and EPC requirements.

> So the client plays a role in terms of setting the ultimate brief…our building has to be a flagship of sustainability; that in itself is not much of brief, it's quite vague. So it's our job to interrogate that requirement and then help the client make an informed choice in terms of how they move that forward.
>
> M&E design consultant (SAW01)

The client was not keen on the biomass option because of operational issues and planning concerns over increased traffic congestion from fuel deliveries.

> Certainly biomass was just frowned upon, right from the outset. They didn't want the hassle of deliveries and manual maintenance and manual handling.
>
> M&E design consultant (SAW01)

Despite over £1m being already spent on a borehole with a view to extracting geothermal energy (this had been done during site clearance), the scheme was no longer held to be feasible in the short term and so the idea of using geothermal heating was dropped. However the M&E design consultant (SAW) made provision for future connection to any local district heating system which might be built as the remaining site was developed. He described how the specification was initially defined by the client requirement for a flagship building for sustainability and then by costings.

> It soon became very apparent that all of these novel, innovative approaches that we were proposing to help them market this building as a flagship for sustainability, were not affordable.…as all of the innovative solutions were falling by the wayside, because of cost, I think the client was thinking, well, we've got to have something to say for this project….They wanted something up there that was visible so the general public could see that there was something that made this building special.
>
> M&E design consultant (SAW01)

In order to obtain a BREEAM Excellent rating, the building was designed to include natural ventilation where possible, mechanical ventilation heat recovery, and innovative lighting. The inclusion of a PV system did not directly gain energy credits for the BREEAM Excellent rating, but reflected how the client's desire for both a visible form of sustainability statement and for an integrated design drove the decision for BIPV.

> 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. Just the look of the building.
>
> Architect (NW01)

The architect (NW) and client were intent on using highly visible forms of sustainable technology and favoured the use of green walls and roof, and PV panels. This choice meant that siting PV on the roof would be difficult. Firstly a lot of roof space had been taken up with the planting and well-watering system. Second, using PV technology would necessitate puncturing the roof membrane to fix the brackets for the PV panels, which might impact water tightness of the roof membrane used with green roof technology. Finally, the parapet designed to enclose the green roof was quite high and would have shadowed the PV panels. To counter this, the panels would have had to be mounted above the parapet height, and as they would then be seen over the parapet, this would be unacceptable to the planners. Because of these concerns and because of worries of risk over water-tightness, the architect

(NW) took the decision to use BIPV on the building façade. He summarised his decision as follows:

> And if we're into that, it's extra steel work..a lot of time you've got to puncture membranes, you've got to puncture your roof. So doing it integrated through the [façade] system took away a lot of necessary coordination and risk.
>
> Architect (NW01)

The architect (NW) had decided to use BIPV on the building elevation and wanted to incorporate it on the large south-east elevation which was visible from the street. The M&E design consultant (SAW) advised the architect (NW) that this would not be a good choice as the façade had already been designed with extensive brise-soleil fins to shade the windows. These would have shaded the panels and reduced efficiency. The M&E design consultant (SAW) and the architect (NW) considered the idea of incorporating the PV into the fins, but rejected this on cost grounds and eventually settled on using BIPV on the smaller south-west elevation, which had no brise-soleil fins. Part of this decision was driven by a discussion with the client over the likely EPC rating of the building. The client was keen for the building to be "A" rated and as it stood, despite achieving BREEAM Excellent, it would only have achieved a "B" rating. The M&E design consultant (SAW) investigated how the BIPV system could improve this rating and calculated that 260 square meters of PV panels would have been required. The client considered the cost implications of using this area of BIPV and decided that a "B" rating would be acceptable, but still insisted on having BIPV as part of the project. A figure of 50 square meters of BIPV was calculated to fit comfortably on the south west façade and the window sizing on the building was designed accordingly. The M&E design consultant (SAW) described the compromise.

> If they put in 260 square meters of roof mounted PV with a hundred square meters of vertically mounted, they would have got an A rated building. But they weren't prepared to pay for that. So what they've ended up with is a PV array of 50 square meters on that southwest façade… The client was still keen to have the PV in one form or another, just to underline the environmental credentials of the building, so it was more visible to the general public. So 50 square meters was like a comfortable fit on that façade; to accommodate 260 square meters on the roof would have been quite a massive undertaking and costly as well.
>
> M&E design consultant (SAW01)

7.2.2 **Episode 1: technological frames**

This section illustrates how the actors viewed the technology through different frames through this episode and how tensions developed over conflicting goals. Figure 7-1 shows how the network of actors, technological frames, problems and solutions played out during the initial design episode and the following description draws attention to the main highlights of the episode.

At the start, the client and the architect (NW) mobilised three different technological frames; Green Guardian (wanting the building to be sustainable), Cost Watcher (wanting to obtain EDRF funding) and Design Aesthete (wanting the building to make a statement). The user (the lettings manager (FS)) shared the Green Guardian frame, as did the M&E design consultant (SAW). In order to get both EDRF funding and be an accredited sustainable building the project team needed to achieve a BREEAM Excellent rating and this became a project goal. As the team carried out the sustainability assessment needed for the BREEAM rating, the M&E design consultant (SAW), architect (NW) and client mobilised the Design Optimiser frame to consider the options for sustainable for technology. As they considered the options, the team used the Risk Minimiser frame to assess the possibilities and BIPV technology. The use of the technology as integrated windows met the criteria of both the Risk Minimiser frame (that the risk for installation would be defrayed onto the contractor, and that

BIPV windows were less risky than using BIPV brise-soleil louvres), and the Design Aesthete frame (the building would have a highly visible form of renewable energy which would make a statement of sustainability). The Design Optimiser frame was mobilised by the team to calculate the total area of BIPV cells necessary to achieve a both “A” and “B” EPC ratings and the Cost Watcher Frame led the team to choose the lower rating, and so the design for BIPV system was settled on 50 square metres of cells.

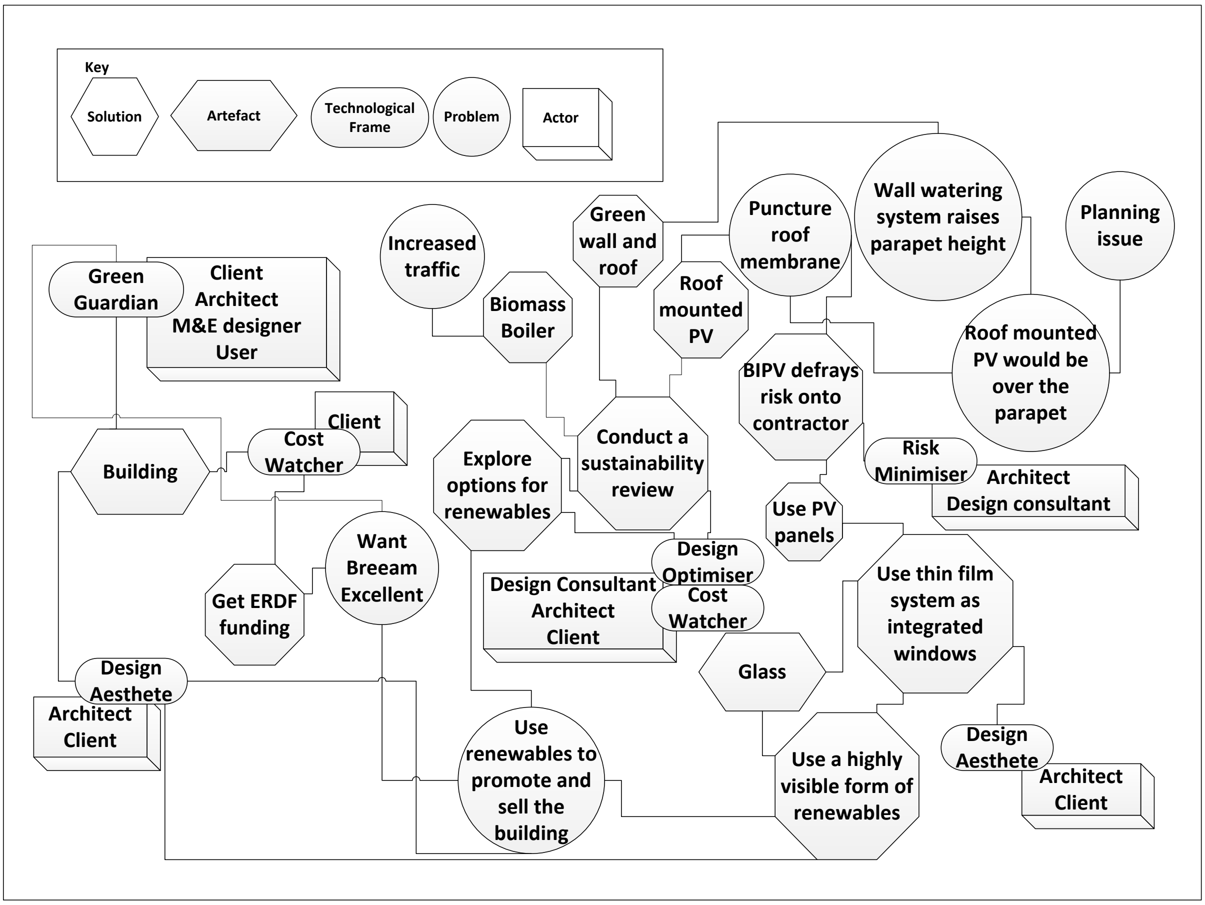


Figure 7-1: Technological frames mobilized in episode 1 (initial design), Future Green

The analysis above illustrates how the technological frames of Green Guardian, Design Aesthete, Cost Watcher, Risk Minimiser and Design Optimiser were all mobilised by the actors during this episode, and how many of the actors related to the technology through more than one frame. This discussion shows how the different goals between actors using different frames gave rise to a combined solution of BIPV windows and a BREEAM Excellent rated building. In this episode, there were no dominant frame and it is interesting to note that the frame of the Generation Maximiser was absent. The Green Guardian frame and the Design Aesthete frames became aligned, with the design satisfying both of these groups, and the BREEAM and EPC ratings of the building becoming a social artefact around which the team focussed.

7.2.3 **Episode 1: co-development**

This episode illustrates how rather than the BIPV or the building being fixed, the BIPV system accommodated the building and vice versa. The summary of co-development during the whole case study is presented in section 7.8.2 but two important elements of the co-development of building and technology occurred in this episode of the project.

i. The two client requirements of a building that made a sustainable statement and a building that qualified for an EDRF award led to the inclusion of BIPV in the building and its integration into the windows of the south west façade.
ii. The use of BIPV in the window glazing directly shaped the dimensions of the windows and their appearance (detailed in episode 2).

7.3 Episode 2: pre-tender design

This second episode follows from the initial design, where both the outline shape of the building and the configuration of the BIPV system had been defined. The pre-tender design episode follows the development of the more detailed system and building design through to the definition of work packages and tender documents. The account begins at the point where the BIPV technology was detailed.

7.3.1 Episode 2: narrative account

The architect (NW) started talks with a glazing supplier (WA) who proposed a thin film PV technology which could be applied to the window glazing and would provide some transparency with a brown, wood-bark appearance. The generation potential of the system was less than conventional monocrystalline technology, but as generation of the PV system was not critical - only the square meterage installed - the architect (NW) adopted this technology as part of an integrated glazing solution. These discussions took palace approximately one year before the tender documentation was released.

The architect (NW) developed details of the elevations of the building and sent elevation drawings to the glazing supplier (WA) to check that the PV glazing would be compatible. Based on his layout, the total area of PV glazing was forty-two square meters. The glazing supplier (WA) indicated that the height of the windows on the drawing would require two panes of glass for each PV window, as the thin film technology had limits on the size of each panel, and suggested standard-sized glazing panels that would fit the outline design. The design was adapted to suit the glazing units, with each PV window having transoms to allow for two standard sized thin film glazing panels to be used, one on top of the other. The glazing supplier (WA) produced initial calculations of the generation potential for the forty-two square meters of PV.

The M&E design engineers (SAW) consulted with the façade supplier (RR) over the PV system and developed a specification for the BIPV, passing this to the main contractor (TH) who had been appointed once the initial design was agreed. The architect (NW) had specified the thin film system from the glazing supplier (WA), and so the main contractor (TH) decided to include the BIPV in the building “envelope work package.” The decision-making process was described by the main contractor.

> That was a contractor decision that we put it into that package, purely because it was specified as a WA system, and WA do double glazing, it was specified as a [WA] PV unit by the architect. So in that sense it made perfect sense to us to put it into the envelope package, because it’s no different to installing any other window, it’s just got the PV components within it.
>
> Main contractor (TH01)

The specification of the “envelope work package” was entrusted to a design consultant (the envelope design consultant) who had no experience of BIPV. He was given the M&E design engineer’s (SAW) specification for the BIPV, which included a requirement for a design portion to be included in the package to indicate that some degree of electrical design and coordination would be required. The envelope design consultant was advised by the architect (NW) and main contractor (TH) to treat the BIPV as essentially a glazed standard window. These two views are illustrated in the following quotes.

> I think there’s a clause in our specification that suggests that 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.
>
> M&E design engineer (SAW01)

> Essentially, the way those PV plans have been put in is they’re just into a double glazed system, so it’s just like installing a window.
>
> Main contractor (TH01)

The glazing supplier (WA) had an ongoing relationship with a façade supplier (RR) and suggested to the architect (NW) that the façade supplier be included in the list of potential suppliers.

The envelope consultant divided the envelope contract into two parts - the architectural part (façade) and the electrical component which included the wiring and inverters. The electrical design portion was included in the main Mechanical and Electrical contract for the building.

7.3.2 **Episode 2: technological frames**

The following analysis illustrates how the different perspectives of actors in different technological frames gave rise to decisions which paved the way for the problems which arose in the later stages of the project. Figure 7-2 shows how the network of actors, technological frames, problems and solutions played out during the pre-tender episode and the following description draws attention to the main highlights of the episode.

The architect (NW) mobilising the Design Aesthete frame had no understanding of BIPV glazing technology and brought in the glazing supplier (WA) to fix the glazing specification. Both these actors mobilised the Design Optimiser frame to develop a solution for the size limitations for the glazing panels. The main contractor (TH) adopted the Cost Watcher frame and elected to split the work packages using standard demarcations between electrical and façade suppliers. This was primarily because he did not adopt the Design Optimiser frame to understand what the technology involved. At this point the BIPV system was split into two assemblages: the glazing; and the electrical system. The contracts or work packages became a social artefact and these three artefacts (the electrical system, the glazing and the contracts) shaped the main contractor's (TH) understanding of the BIPV system. Interestingly the Generation Maximiser frame was not mobilised at all in this phase.

In this episode one difference to highlight from the previous case study is the lack of understanding between actors adopting different technological frames. The main contractor (TH) was fixed on the goal of getting work packages assigned quickly and so missed an opportunity to keep the BIPV system as one package.

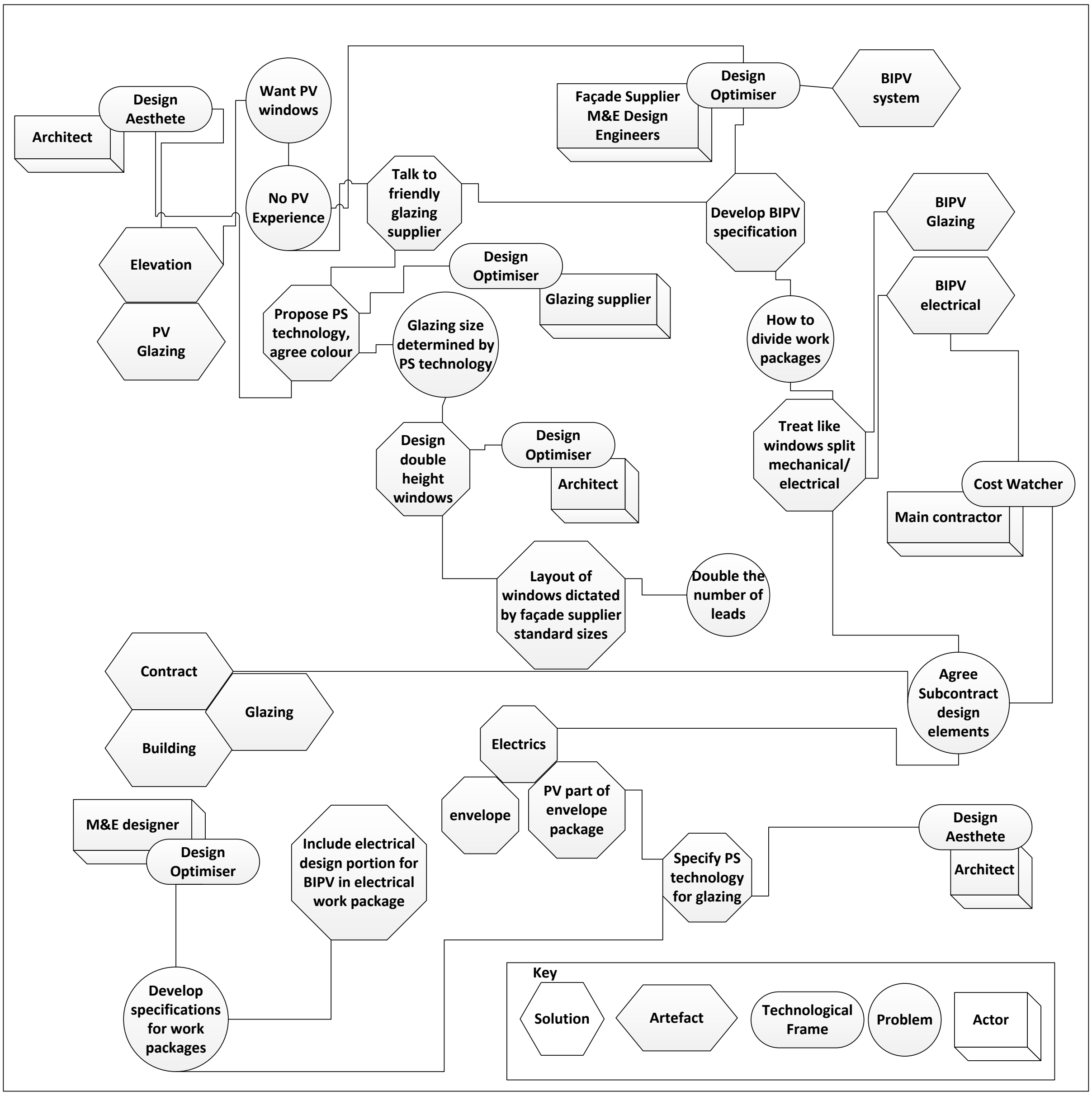


Figure 7-2: Technological frames mobilized in episode 2 (pre-tender), Future Green

7.3.3 Episode 2: co-development

During this episode of the project there was one example of the mutual articulation of the building and the BIPV system, and one example of a standard procedure influencing the design of the BIPV system.

i. The use of thin film PV technology restricted the size of glazing panels that could be used. This meant that the architect modified the window design for the whole building to accommodate this restriction. He designed double windows with glazing bars between the glazing panels, to achieve larger window openings.
ii. The main contractor chose to include the BIPV glazing panels within the "envelope work package" and to separate out the electrical work into the main electrical contractor's work package. This standard procurement process for work packages de-coupled the BIPV system and shaped the design (or non-design) of the whole BIPV system from then onwards.

7.4 Episode 3: tender process

This episode follows on from the point at which the tender documents were sent out to contractors and continues up to the point when work contracts were awarded.

7.4.1 Episode 3: narrative account

Over the period of the tender process, the UK feed-in-tariff for solar energy was cut and the UK demand for solar panels fell by seventy percent. The glazing supplier (WA) dramatically scaled back its involvement in solar panels and stopped offering thin film technology. The glazing supplier (WA) offered the architect (NW) traditional monocrystalline laminated PV panels, which would provide slightly superior PV generation but which were more like a chess board in appearance. The PV cells in the laminate would be black squares (16cm^2 each) and transparency would be provided by the spaces between the PV cells, rather than as a general translucency across the whole panel.

The architect (NW) was unfamiliar with the differences in the two technologies and accepted the change in technology. He summed up his view of the situation as follows.

> The only difference as far as I know with that is the graphical display of the cells, …the traditional PV stuff, 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 architect (NW) and main contractor (TH) were keen to keep to the schedule and agreed that the new technology be used. The new PV glazing units were available from different suppliers and the choice of glazing unit supplier was left to the façade contractor (RR).

The envelope consultant who developed the M&E contractor package was unfamiliar with BIPV. He drew up the specification to include spurs to the inverters and included a clause in the tender document requiring the use of a specialist installer who was familiar with BIPV. The M&E contractors who were selected to submit tenders were also all unfamiliar with BIPV.

7.4.2 **Episode 3: technological frames**

In this episode the Design Aesthete frame and the Green Guardian frame were not evident. The other technological frames of Design Optimiser, Cost Watcher and Time Sentry were mobilised by the actors who were concerned with getting work packages drafted and tender packages worked out. The architect (NW) viewed the substitution of technology as a risk to time, rather than as an aesthetic or user matter and did not understand the impact that the new technology would have on the aesthetics or functionality of the building.

The SCOT diagram of the mapping of frames, artefacts, problems and solutions Figure 7-3 reflects the apparent isolation with which decisions were taken and shows the surprising absence of input from actors adopting the Design Optimiser and Generation Maximiser frames. It would appear that the most dominant frames in this episode were those of Cost Watcher and Time Sentry and the social artefacts of contracts and tender documents.

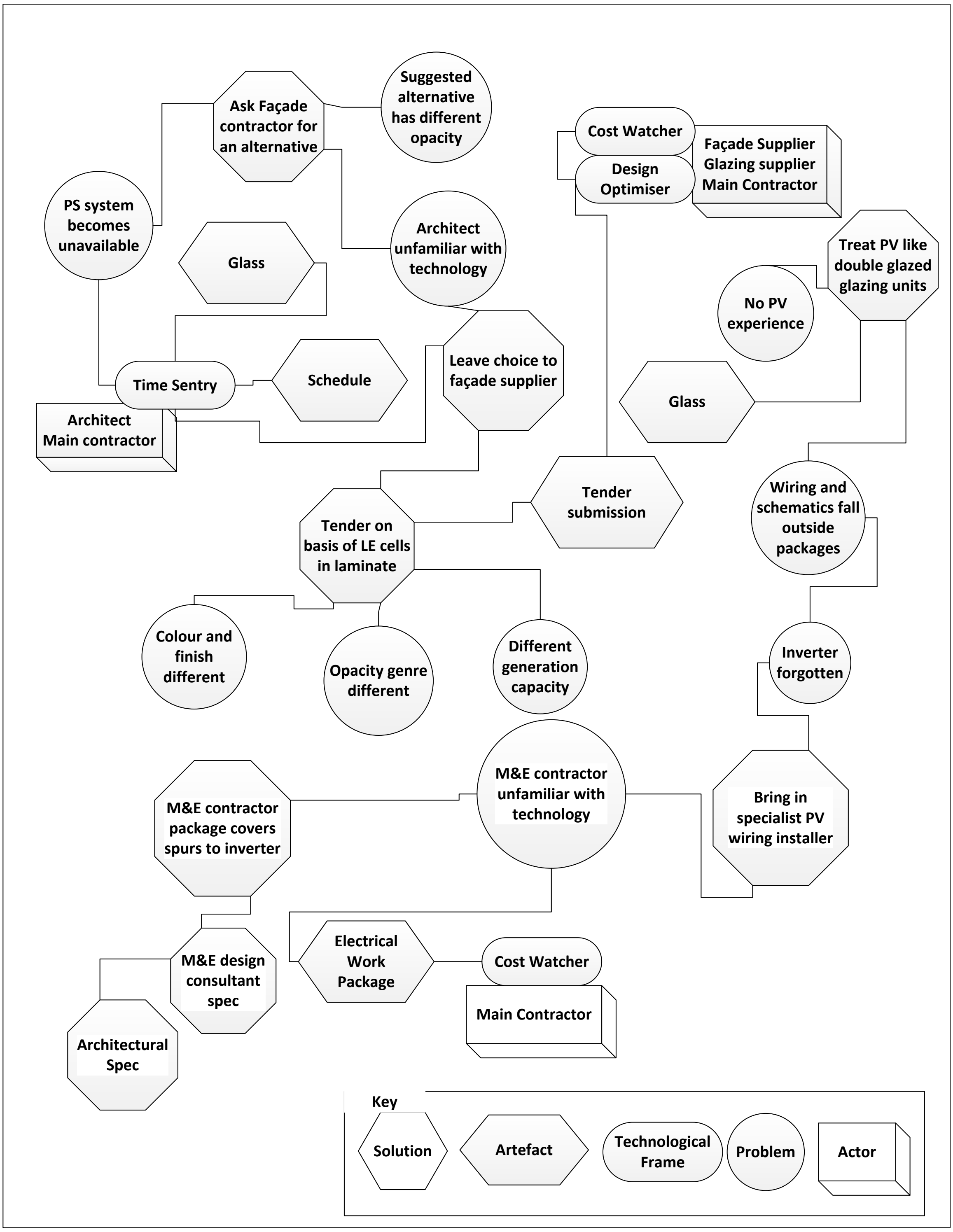


Figure 7-3: Technological frames mobilized in episode 3 (tender), Future Green

7.4.3 Episode 3: co-development

The architect (NW) paid little attention to the single co-development event in this episode, but it dramatically altered both the building and the BIPV system and it clearly illustrates the co-development. When the thin film glazing was replaced with conventional monocrystalline laminate panels, the BIPV system characteristics changed, but so also did the physical appearance of the building. Before, the windows were to have been a translucent bronze and afterwards the windows had a black, chess board appearance. The difference from within the building was even greater. Previously users would have been looking through the windows with a bronze translucency. Now they would see a dark matrix of PV cells and junctions within the laminate.

7.5 Episode 4: detail design

This episode starts at the issuing of contracts and follows the design of the BIPV system and façade. It finishes at the point that the façade system (including the BIPV glazing units) were delivered to site for installation.

7.5.1 Episode 4: narrative account

The contract for supplying the façade was won by RR who used the glazing supplier (WH) as a sub-contractor for all the glazing units on the envelope. The BIPV units formed a very small part of the glazing sub-contract. The façade supplier (RR) confirmed the dimensions of the BIPV glazing units and asked the glazing supplier (WA) for layout drawings showing the layout of the PV cells (the grid) and the offsets where the PV wires would enter the frames. The façade supplier (RR) was concerned to agree the visual effect of the BIPV panels with the architect (NW), and to get the go-ahead for placing an order for the glazing units. The façade supplier (RR) describes the importance of the layout.

> If you want to have even spacing on the photovoltaic squares then you've got to take into account that that window's going to glaze in there by say 80mm, or whatever. So you've always got to produce a set of elevation drawings, so when that one sits on top of that one and gets glazed into the window you get left with what should be an even margin all the way around the edge of the frame. So there's a bit of setting out has to go on between both companies and also with [the architect] as well, because they were very particular that they wanted to keep an even band around the edge.
>
> Façade supplier (RR01)

The architect (NW) was very concerned about the detailing of the cell spacing and in particular about the placing of a small logo with the PV laminate supplier's name (LE) and the kite mark for toughened glass. The architect was insistent that the logos should all be at the top of the glazing on a particular side. This entailed moving some cells around and making sure that each panel was individually laid out. The PV laminate supplier (LE) had to spend time in optimising cell spacing to try to maximise output, and then liaised with the glazing supplier (WA) to ensure that the wiring connectors were located in the correct place. The PV laminate supplier (LE) went on to describe the way that the architect (NW) drove the layout from the aesthetic perspective.

> I remember he wanted the LE logo in a certain place on each panel. So that means we had to alter something else…[it was]: Oh, no, I want them all in that corner. So where we could have made six panels and you could have had some there and some there we then had to say, right, well, six individual panels, so we can put them all there. So we had to alter cell spaces like that as well so we got the look he wanted. There was, definitely, [a lot of to-ing and fro-ing] over 5mm here, 5mm there. Logo position here, logo position there.
>
> PV laminate supplier (LE01)

This level of detailing and layout considerations of symmetry put back the signing off of drawings and delayed the delivery of the PV laminate panels.

> I think the delay was because of the spacing that the architect wanted round the panels, because...if they want different connection arrangements we then have to make new drawings.
>
> PV laminate supplier (LE01)

From the façade supplier’s (RR) point of view, the main issue around layout was to agree the position at which the wires from the PV laminate were going to penetrate the frames. It is clear from the following quote that he viewed the discussions as part of the normal process of window design, rather than anything particular about BIPV.

> So the setting out was all very discussed…so it did go back and forward a couple of times as any setting out does, and just a wee bit of tweaking here and there, and just where the wires were going to come out for getting wired up within to the window frame.
>
> Façade supplier (RR01)

As the drawings were going through the approval process, the main contractor (TH) asked for a check on the generation potential of the panels against the original specification from the glazing supplier. At this point the glazing supplier (WA) saw the side elevation drawings of the façade rather than just the front elevations and realised that the architect (NW) had designed all the windows with a 250mm reveal. The glazing supplier (WA) ran a new set of calculations and these showed that during substantial periods of the day the reveals would shade the PV cells and reduce generation in each affected window to almost zero. This problem was discussed by the architect (NW), glazing supplier (WA), M&E designer (SAW) and main contractor (TH) and each had a different view of the problem and how it should be resolved.

The architect (NW) was clear that the windows were there to make a statement, that the reveals were a necessary part of the design, and that the PV panels within the windows were part of the statement.

> So by pushing those windows forward it would have obviously had a major impact on the elevation; it would have had a major impact on the actual construction sequence, because the whole detailing would have changed with the envelopes; or it would have had big impacts on the appearance and on the construction detailing anyway…And we didn't want to go back and just start sticking things on the roof, because they weren't there to provide electricity. If we put them on the roof no one would know they were there anyway. So that was the bigger issue on the main building façade in public view everyone could see them and it's a selling point of the building.
>
> Architect (NW01)

The M&E designer (SAW) took the view that the windows should be redesigned to allow the system to work properly.

> It was discovered that the [PV] panels had been recessed too far into the windows. So, for a large amount of the year, they're going to be overshadowed and won't be generating very much. ..My advice was, well we can't stand by a solution which we know isn't going to work. We know that it's not going to generate much electricity, but if you're spending a few thousand pounds on the installation, you want it to generate as much as it possibly can. You want to get the most out of the installation, acknowledging that it's not going to be a lot. As opposed to if it's not going to generate anything, you might as well rip out all the electrics behind the scene and just have it there as a billboard…Well my view was, we have to solve this problem and we can't sweep it under the carpet, we have to be open and honest about it...I suggested, could it be pushed forward? Could it be put on some sort of bracketing system that would make it flush with the façade, as opposed to recessed? And I think that was just considered not viable.
>
> M&E design consultant (SAW01)

The main contractor (TH) was concerned on two fronts - firstly that the client should be well served by the technology and second that the schedule would not allow for any changes to the system of mounting the glazing units. The glazing supplier (WA) remembered the calculations but was not aware that this had caused major issues.

> There are issues with shading on the panels and reducing the efficiency of the panels.… it was never there to create a certain amount of energy it was never really such an issue on that one ….to some extent I think it could almost wipe out a whole run of cells that are all linked together. It didn't just affect a certain percentage.
>
> Glazing Supplier (WA01)

The reduction in electricity output could not be quantified, as the generation figure had not been revised when the technology had changed from thin film to monocrystalline cells, and the architect did not feel able to resolve the issue.

> That's when the conversation started - well this is what we said originally, but then no one told us what we then were going to get so we couldn't make a comparison anyway. We never found out those figures….the original specification was [thin film] and that was what that original figure was based on, so we had [not] got the figure.
>
> Architect (NW01)

The design of the windows and glazing was left as it was and the design continued to installation.

During the design phase the main electrical contractor was not given wiring diagrams for the window strings and was also not provided with any details of PV outputs to allow sizing of the inverter. The M&E contractor (BSW) delayed appointing a PV wiring specialist and effectively shelved the design of the BIPV wiring.

7.5.2 **Episode 4: technological frames**

As the façade supplier (RR) and glazing supplier (WA) worked through the detail of the layout of the PV cells, connectors and junction boxes, they shared the Design Optimiser frame and as in other cases this appeared to result in a collaborative mode of problem solving, very different from the isolated modes seen in previous parts of the project.

However the architect (TH) stuck to the Design Aesthete frame and became very taken up with the minutiae of the position of the laminate supplier logo. So much so, in fact, that the laminate supplier had to request sign-off on the drawings in order to meet time and cost issues. Contracts in the form of social artefacts became an important factor again when the main contractor (TH) asked for the generation figures to be checked against contract. At this point the team realised that there were no target generation figures in the design - no-one had calculated a revised generation forecast after the technology had been changed. The glazing supplier (WA) tried to check the figures - mobilising the Design Optimiser frame - and then realised that the reveals on the windows would over-shadow the PV glazing units and at particular times of each day would reduce generation to almost zero. When trying to resolve this issue a polarising of technological frames happened - the main contractor (TH) wanted to give the client a working PV system (Green Guardian) whilst also wanting to keep the project on track (Time Sentry). The architect (NW) also wanted to keep the project on track, but mobilised the Design Aesthete frame to insist that the design remain with the large reveals, as they made a strong architectural statement. The M&E design consultant used the Green Guardian frame as he argued that the technology should generate electricity. The impasse was broken as the main contractor and architect prevailed, mobilising the Time Sentry frame, and the deep window reveals remained in the design. This is reflected in the SCOT diagram (Figure 7-4) which shows that the dynamics of these decisions.

This episode demonstrates that collaborative problem solving appeared to occur when the Design Optimiser frame was shared by two or more actors and that conversely, when an actor stuck rigidly to his single frame, then delay or an impasse was likely to arise. The impasse over the serious issue of reduced (almost zero) generation was moved forward by the Time Sentry frame which focussed attention on the schedule. This again illustrates the role of social artefacts in the decision-making processes.

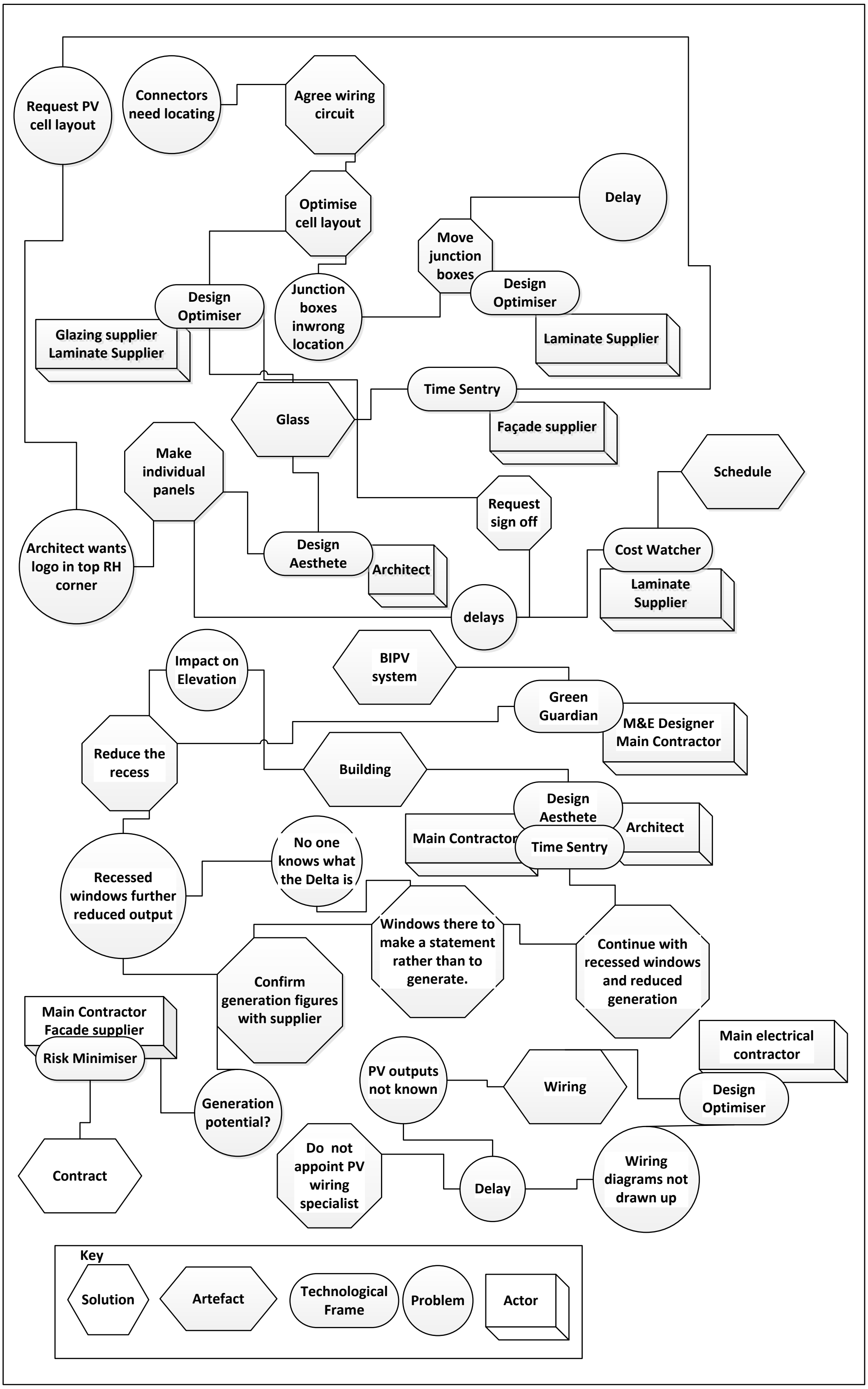


Figure 7-4: Technological frames mobilized in episode 4 (detail design), Future Green

7.5.3 **Episode 4: co-development**

Two clear examples of co-development of the building and the BIPV system occurred during this episode of the project. Neither was particularly noticeable when viewed from ground level, but both had very major implications on the installation and performance of the BIPV system.

i. Minor examples of co-development occurred as the position of PV connectors, cells and connector strips determined the position offsets and junction boxes of the frames and vice versa.
ii. The deep reveals around the windows shadowed the PV cells within the glazing and reduced the performance of the BIPV system. Although not an example of physical co-development, the reveals had a major impact on the BIPV system performance.

7.6 Episode 5: installation

This episode starts as the façade was delivered to site and continues through the installation and commissioning process.

7.6.1 **Episode 5: narrative account**

This episode started as the PV glazing arrived on site and the main contractor faced the job of trying to understand how the BIPV cables would fit together. The main contractor (TH) described the situation in the extract below.

> These turned up onsite with the tails, and that was the first time we really realised, oh, right, so we've actually got, we've got four tails sticking out of all of these units that we need to connect up…Now we didn't know that it was going to come like that till it landed onsite. So part of the challenge for us was working out, what does that connect to? Is that coming down to this one?
>
> Main contractor (TH01)

The glazing units had been delivered to site by the glazing supplier (WA), but installation was to be carried out by the façade supplier (RR). The glazing supplier had not been asked to provide wiring details and had simply supplied layout drawings showing the points where the flying leads would be positioned.

> Because we also then had to drill our frames to let these wires come out so somebody else could wire them up. We don't get involved in any of that, we purely put the window in and leave a tail for somebody else to come along, which is M&E. …we dealt with [the main contractor] and we handed over all these drawings, obviously the sectional drawings and they dealt with it direct for themselves under the M&E contract because at the end of the day we just leave a tail and they take it from there.
>
> Façade supplier (RR01)

The initial wiring details had been worked out worked out between the glazing supplier (WA) and the PV laminate supplier (LE) in some detail.

> Then we had to design that to fit, but also the [electrical] connections so they then interlinked from panel to panel. So there's quite a bit of design work in that…we work with WA. They would say, right, this is how we think we're going to wire it together, so then we had to look at our cell layout and then alter where we put the junction boxes so we could connect it together.
>
> PV laminate supplier (LE01)

This had not been passed onto the main contractor (TH) who had to try to judge the best way of running the cables.

> Because the windows are staggered as well, we couldn't just wire them up this way and then do a loop and come back down. So they had to cut across…..we actually had to drill through all of the window frames to bring the cables out, and then put the glazing beads on... So the cables are actually coming through the frame. They were then linked, and there's a spur. Now is it on every window - to the left hand side we have a spur. And they were all jointed to the wiring, and then basically all linked back down.
>
> Main contractor (TH01)

The issue was to try and connect wires between the irregularly spaced windows in a way that minimised the number of penetrations though the façade and which allowed efficient connection of the strings of cells. The architect (NW) did not see this as an issue and was concerned with reducing the appearance of any internal wiring.

> But the wires within the glass itself…we didn't have any major problems with. As long as it was done effectively, neat and tidy and to the best ability, I don't think we have any problems with it. And obviously the wires could be concealed the best way we can; but if they're an integrated part of the system and they have to go where they need to go that's the system itself.
>
> Architect (NW01)

The solution to the problem was to drill through the glazing frames, pull through the wires and chase them into the surrounding plasterboard. The holes in the frames had to be large enough to pull the connectors through and to minimise the size of the holes, the main contractor (TH) was tempted to cut off the connectors and refit them once the wires had been pulled through, but decided not to do this because of worries of risk and responsibility.

The issue of the wiring configuration and method of getting the wires from the outside to the inside of the façade involved the coordination of four contractors and a delay of over six weeks to the internal finishing. For the main contractor (TH) the issue was delay. Until the configuration and method had been agreed, the internal finishing could not be completed.

> But it did delay us internally, in that we couldn’t close up this elevation on the inside…Because we hadn’t foreseen any of these things, it probably held up this elevation about six weeks…. But it meant we had to leave all of this off internally. We couldn’t seal any of this up until all these were in, all of this was drilled through, these were all wired up. We couldn’t actually close off internally any of these units until all that wiring was done.
>
> Main contractor (TH01)

The leads were all positioned at the centre of the top of the widows so each one had to loop around to the internal plasterboard

> It would’ve been much better if the tails had been top and bottom. Which would’ve been very simple for them to do. Why do they come out of the middle? I don’t understand that.
>
> Main contractor (TH01)

The design of the two-part windows proved even more problematic, as the number and location of the flying leads precluded the option of hiding the leads in the plaster work.

> Well what was even worse is where you’ve got these double lights fixed together. And so you’ve got that…got four tails there …in the middle of the glass. So we’re saying, all right, we can take these out into the plasterboard, and hide them. How are we supposed to connect these up? Because it was just purely on the glazing and the window frame…So we ended up having to drill holes top and bottom, feed this one up, kind of take it up between the gap between the glazing and the actual frame itself. We had to feed the cable up like that, pop it through, back down, and do the same on both sides to connect them up.
>
> Main Contractor (TH01)

When the façade supplier (RR) came to fit the stop beads to the glazing panels it became clear that the beads were of the wrong size.

> The other issue that hadn’t been picked up…is those units are a slightly thicker unit. So all the stop beads that came were wrong. And these were anodised. So they all had to be shipped away and new stop beads made. … So we ended up having to timber chock them all in for about six weeks while the stop beads were [re-made], and you can’t fit those until all the wiring’s done.
>
> Main Contractor (TH01)

The glazing supplier (WA) and façade supplier (RR) had designed the stop beads using the normal thin film glazing thickness rather than the monocrystalline technology which used laminated PV panels which were 2mm thicker.

Once the panels were in place and the wiring configuration had been agreed, the M&E contactor (BSW) began to connect the cables. It then became clear that the M&E contactor (BSW) had forgotten to order the inverter and had not employed a specialist PV wiring contractor. The PV wiring contractor was employed, but could not order the inverter as the output of the PV system was needed to size the inverter and maximise the system efficiency. In the end a pragmatic solution was agreed between the main contractor (TH) and the PV wiring contractor. The inverter was sized for a theoretical maximum output from the square meterage of the glazing panels.

> They’d got a window with the PV on it, but nobody took the design any further, to say well, what size inverter are we going to put on this thing? ..So basically we had to get an individual company in, and we give them the square meterage of the windows and asked RIAS [a specialist inverter supplier] what sort of inverter that we would put on that, because they’re the specialists. They advised us of the inverter based on that square meterage, providing it was based on a nice sunny day and it was in the right position. They couldn’t do the calculation with it in situ as it was.
>
> Main Contractor (TH02)

The inverter location had not been decided in the initial design. There had been talk of having a panel on display in the foyer of the building, but as the very small amount of electricity generation became apparent, this idea was shelved and the architect (NW), M&E design consultant (SAW) and main contractor (TH) decided to put the inverter in an area which would not be seen. This process was described by the M&E design consultant (SAW).

> TH02 came up with the idea of locating the inverters within some of the rooms which became spare after the ICT strategy changed. So there were some small rooms that run up alongside the staircase where he suggested putting in the inverters for the system. In terms of monitoring the electricity production, originally there was, I think, a proposal to have some sort of kilowatt hour meter within reception. When this problem came to light I think the kilowatt hour meter was value engineered out.
>
> M&E design consultant (SAW01)

It was left to the main contractor (TH) to site the inverter and to find a place that was inconspicuous but which would keep the cable runs as short as possible to reduce system losses.

> The siting of the inverter was never shown on a drawing, we've tried to put that close as we can to the cable, and then run from there back to the distribution.
>
> Main contractor (TH02)

The M&E contractor (BSW) queried the proposed siting of the inverter and suggested that it was too far away for an efficient system, but the electrical contractor's site supervisor decided to stick with that location.

> We had an electrical project engineer who also raised that query i.e. the distance as well. It got raised and it got OK-ed, so basically it was up to BSW02 to decide how he was going to run those cables.
>
> M&E Project Manager (BSW01)

The inverter was eventually sited in a cleaning cupboard off the entrance foyer of the building.

7.6.2 Episode 5: technological frames

As the glazing units and façade assemblies arrived on site, the main contractor (TH) was concerned with delivering the installation schedule and was invested in the Time Sentry frame. When the façade supplier site supervisor (RR) tried to install the glazing panels in the frames, he realised that the two trailing wires would not fit within the frame in such a way that would allow the wires to end up on the inside face of the panels. The glazing supplier (WA), façade supplier (RR) and main contractor (TH) all shared two frames - Time Sentry and Design Optimiser. They were keen to solve the problems and move on with minimum delay. This combination of frames appears to have pushed a solution through and allow the project to move forward. Interestingly the one solution that might have been the simplest - cutting off the connectors and pulling the bare wires through before reconnecting the connectors was ruled out because the main contractor (TH) perceived it as possibly invalidating a contract (Risk Minimiser).

In a similar way, the issues with the missing parts of the electrical design were solved as the M&E contractor (BSW) and electrical subcontractor adopted a combination of Design Optimiser and Generation Maximiser frame to determine cable runs and the inverter size. Interestingly, this was the only occurrence of the Generation Maximiser frame in this episode. This reflected in the SCOT diagram Figure 7-5 which shows that the dynamics of these decisions

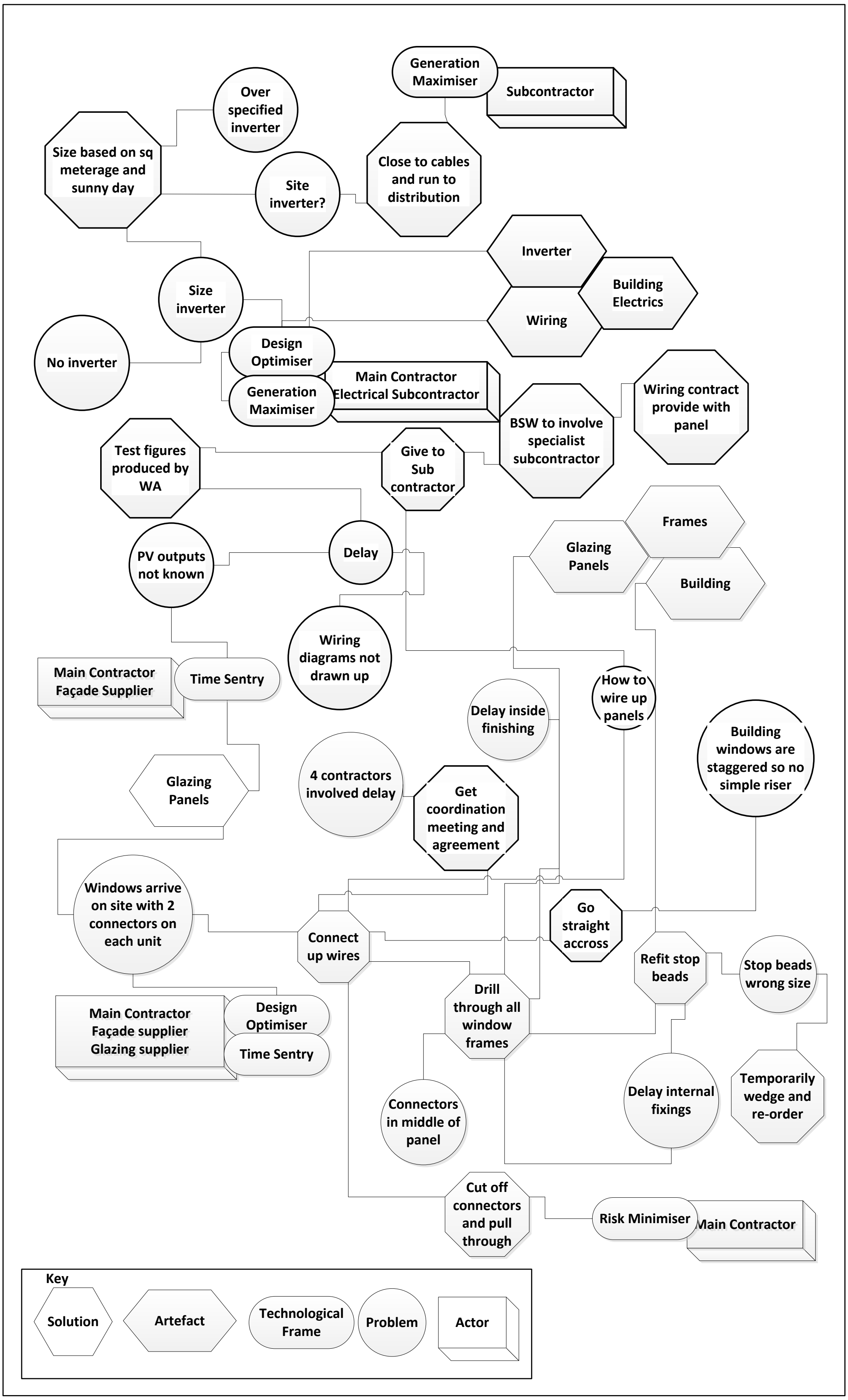


Figure 7-5: Technological frames mobilized in episode 5 (installation), Future Green

7.6.3 Episode 5: co-development

In this episode there were three examples of co-development between the building and the BIPV system

i. The minor mutual adjustment between the frames and glazing units and glazing bars to bring the wires to the inside of the frames resulted in major delays to the closing off of the internal elevation. The origin of these difficulties was in the original discussion of the layout of the frames between the façade supplier and the glazing supplier. They had not appreciated that the arrangement that they settled on would make the wiring difficult for the double height windows. The change in technology actually made the double window design unnecessary, but the architect had not picked this point up and kept the double height window feature.

ii. The inverter sizing depended on the output of the BIPV panels, but the deep reveals shaded the panels at some points during the day and made the output variable. The contractor sized the inverter for his estimate of the maximum output, but this oversizing for other parts of the day further reduced the efficiency of the system.

iii. The reduced performance of the BIPV system affected the siting of the BIPV meter and changed the focus of the building from a prominent generation meter, to a meter hidden in a cupboard away from public view.

7.7 Reflections on the finished building

This case study was the only project to be finished and handed over to the client during the interview period. Many of the interviewees reflected on the finished building and had very different views about the inclusion of BIPV, its execution and appearance. These reflections inform the analysis and are therefore included below.

The architect (TH) was satisfied with the statement that the cells made and did not see a great difference between what would have been delivered by the thin film technology and what the monocrystalline cells delivered.

> It was exactly the same…as far as we know it's just a filling which is applied to the glass within the glazing, but it's just what that looks like...It was more of a bark wood type that we originally specified…. but WA stopped doing that product as this come to site, so it wasn't a massive issue, we just went back to an alternative specification.
>
> Architect (NW01)

The main contractor (TH) was unhappy about the lack of generation potential and was concerned about the internal visual appearance of the windows. The M&E design consultant (SAW) felt that the visible BIPV and the poor generation figures were in tension and would cause issues in the future.

> The building is going to be flagship of sustainability and [if] you get some experts in the field who might look round the building, they will spot this issue straightaway. It's sort of a cardinal sin to have PV which are almost permanently overshadowed. …you don't want it to become a laughing stock of the industry press, saying a flagship sustainability building doesn't generate any electricity using photovoltaics.
>
> M&E design consultant (SAW01)

The M&E design consultant (SAW) had seen the windows in situ and commented on the opaque nature of the windows.

> It's lots of strips, you don't have any panoramic views… you don't have a single piece of glazing which has got any width to it… you'll see a lot of light coming through the gaps between the cells but, which makes the cells look black. It doesn't look ideal...you certainly notice that you've got something on the window, because it is a very substantial black, if that makes sense."
>
> M&E design consultant (SAW02)

The client and letting agent felt very ambivalent about the panels - the letting agent understood that the BIPV had been part of the solution to obtaining ERDF funding, but felt that the appearance of the panels was actually a hindrance to letting the offices.

> The reason these offices are let is simply because they're non regular…not cellular, unlike ordinary offices on the floor. So it's just a little bit different and it makes it a good open-plan kind of space. It's nothing to do with the PV panels, I would say that has reduced the let-ability of it, rather than improved it.
>
> Lettings manager (FS01)

7.8 Summary

This final section of the chapter brings together the five episodes to examine the case as a whole - exploring the technological frames and RSG's, the co-development of the BIPV and the building as the project proceeded, and the issues and challenges which were particular to this project

7.8.1 **Technological frames**

The preceding analysis for each episode within the project illustrated how the technological frames were mobilised by the actors in the project. It went on to explore how tensions played out between the actors mobilising different technological frames as they found solutions to problems. This section summarises the pattern of technological frames used and investigates the way that actors mobilised different frames at different times throughout the project.

This case study was dominated by the Design Aesthete and Cost Watcher frames. After a very brief appearance, the Green Guardian frame disappeared and only appeared on one further occasion, when the issue of the deep window reveals was brought into focus by the glazing supplier. The Generation Maximiser frame surprisingly only appeared once - at the end of the project, as the electrical contractor tried to size the inverter. Three of the most used technological frames were those of the Cost Watcher, Time Sentry and Risk Minimiser and the mobilisation of these frames resulted in finding solutions which followed typical construction project procedures.

There were several examples of actors seeing the technology through more than one frame and this increased interpretive flexibility and aid problem solving. Collaborative problem solving occurred when the Design Optimiser frame was shared by two or more actors; conversely, when an actor stuck rigidly to his single frame, delay or an impasse was likely to arise. This is illustrated in particular in the case of co-development of the frames and glazing units, when the façade supplier and glazing supplier used the Design Optimiser frame to develop solutions, whilst the architect stuck to the Design Aesthete in detailing the cell layout and caused delays to the project.

Another striking feature of this case study is the effect of social artefacts such as the contracts and schedules and how these affected decision-making. In this case study, it was clear that the BIPV system was represented as different artefacts to different actors - the architect saw the BIPV system as glazing panels, the main contractor viewed it at one point as windows, and at another as two contracts or work packages. It was never viewed as a system of components.

Unlike the first case study, there were few examples of actors changing the technological frame through which they viewed the technology during the course of the project. This relative stability echoed the lack of understanding between actors adopting different technological frames, and resulted in the relatively isolated mode of decision-making that was striking throughout the project. The architect in this case study primarily mobilised the

Design Aesthete mode and occasionally the Time Sentry frame. There are a few examples of him adopting the Design Optimiser frame, but these are rare. In general, if the actors mobilised a second frame, it was generally one of the Time Sentry, Cost Watcher or Risk Minimiser. The different frames mobilised by the actors at different times of the project is illustrated in Figure 7-6 below. Actors (the right hand column) moved between frames as the project progressed (the time element of the project being represented on the horizontal axis at different project stages). Some examples of an actor adopting a second or even a new frame did occur - for example the client from Green Guardian to Cost Watcher frame after the pre-tender phase was completed. These shifts could be accounted for by several factors: the natural change in focus of the project actors as the project moved through RIBA stages from concept to installation; the stabilisation of certain elements of the design (for example the size of the glazing panels); and shifts in the nature of the problem (as the PV glazing panels became an aesthetic design issue and then became a constraint for the installation of the frames). Chapter 9 will explore these factors further by comparing the different case studies.

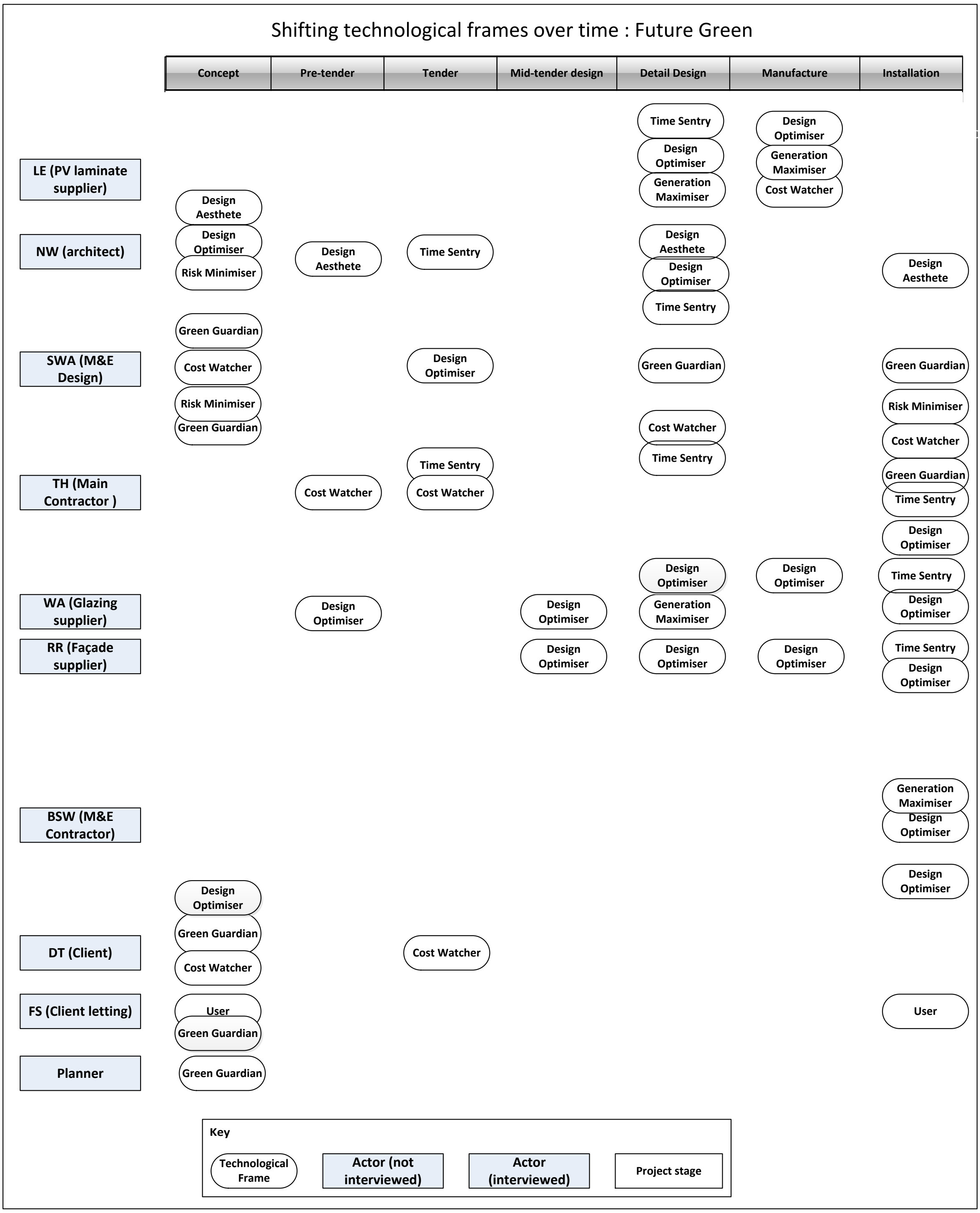


Figure 7-6: Movement of actors between technological frames as project proceeds

7.8.2 The co-development of the BIPV and the building

The discussion of the five episodes in this case signalled a number of key moments of co-development. The discussion which follows explores the co-development story of the building and the technology in greater detail, and shows how this mutual articulation occurred. The three types of co-development identified in the previous case study (lock-in, homogeneity of appearance, and mutual adjustment and adaptation) were also present in this case, together with unfolding innovation, as the BIPV was integrated within the building. The analysis which follows describes the co-development of the BIPV system and the building, from the perspective of key design decisions and the socio-technical network which supported them. The diagrams below 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. Figure 7-7 shows how the process of co-development occurred over the project and illustrates the key stages of the story.

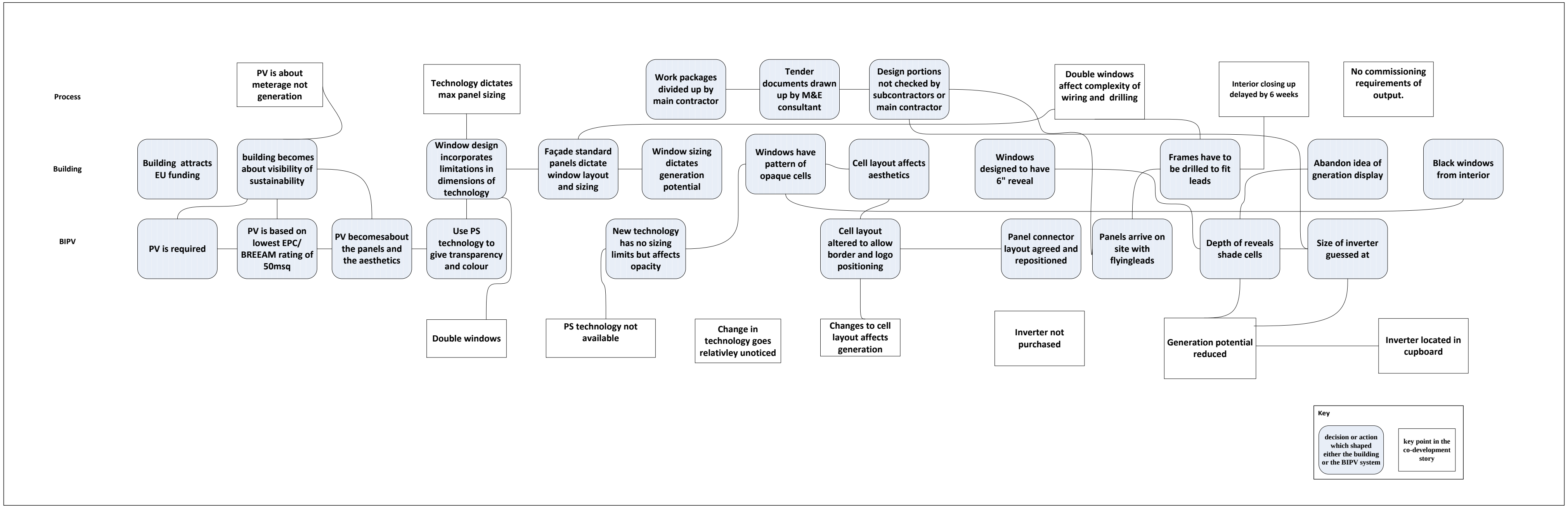


Figure 7-7: Co-development diagram Future Green

Enlarged sections of the diagram are used to illustrate specific points in the discussion which follows. The integration of BIPV is analysed as a succession of problems and solutions which led to the integration of BIPV within the windows as a distinctive element of the glazing. In the early stages, the architect proposed using thin film PV technology. During the tender phase, procurement problems led to their replacement with conventional monocrystalline cells. However the knock-on effects on frame design and glazing beads were not picked up until well into construction, resulting in delays and re-work. The discussion below traces this co-development and decision-making process as it unfolded.

Lock-in

Lock-in occurred right at the beginning of the project when the clients were keen to attract European Regional Development Funding (ERDF), which meant that the building had to achieve a BREEAM Excellent rating as well as an Energy Performance Certificate (EPC) rating of at least “B” and preferably “A”. EPC ratings of both “A” and “B” required the use of renewable technology. At the same time 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”. Lock-in occurred when the client and architect saw that BIPV on the south elevation could deliver both requirements and therefore selected the technology.

The M&E designer calculated that the building would need 260 square metres of photovoltaic technology to achieve an EPC rating of “A”, but only 50 square metres to achieve a “B” rating. The client elected to go for the “B” rating and after discussions with the M&E designers the architect locked-in the decision to use BIPV in the windows of the South elevation of the building. The architect also locked-in the decision to use thin film technology. Figure 7-8 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. This decision then changed the frame through which the actors viewed the technology from one of electricity generation to one of visibility, which drew the architect and designers to using BIPV in the windows and so made the choice of thin film technology logical.

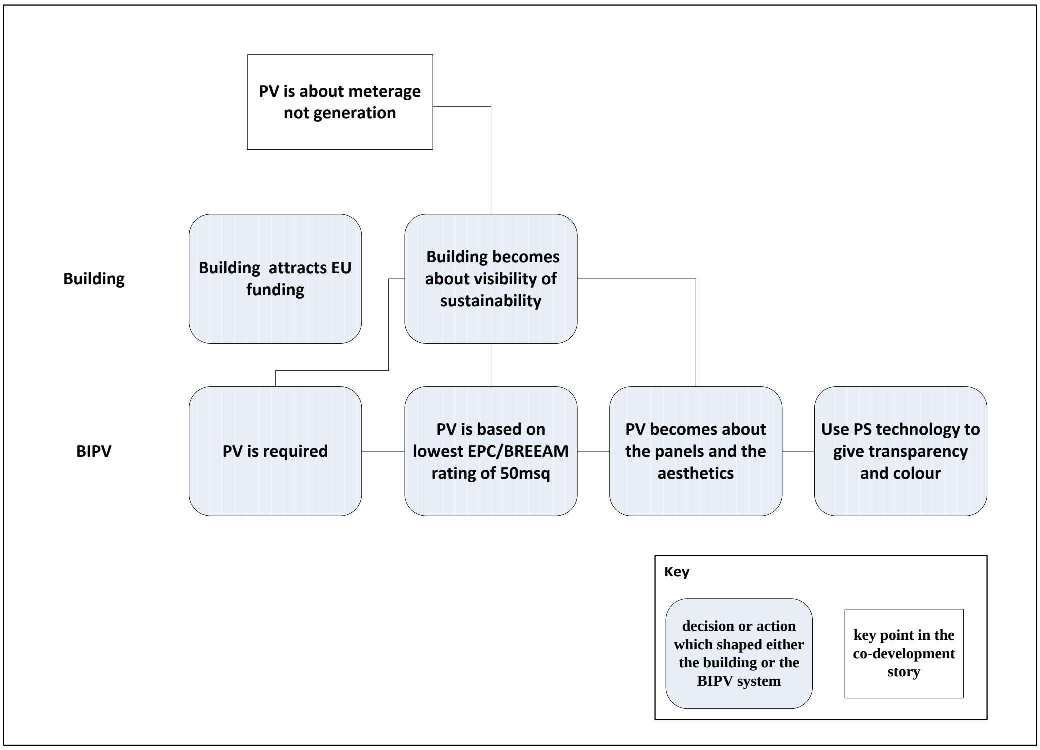


Figure 7-8: Co-development-lock-in

The mutual adjustment of building shape and BIPV design

The mutual adjustment of building shape and BIPV design occurred mostly on site and resulted from problems in the lack of integrated design between the glazing panels and façade frames. These were mostly caused by the change in BIPV technology, from thin film to monocrystalline laminate. Figure 7-9 shows how during the construction phase the lack of design and coordination of the BIPV system led to decisions being taken rapidily over frame modifications, glazing beads and wiring configurations. The glazing panels were delivered to site with two trailing leads on each unit. The units had to be assembled into the frames with the leads ending up on the internal face of the frames. As a result the frames had to be drilled to allow the leads to enter the building and connected to the BIPV wiring. In addition, the monocrystalline laminate glazing panels were thicker than the standard glazing panels and the specified glazing beads for the window units were too thick. This series of adjustments resulted in delays to the schedule and internal finishing of the south elevation.

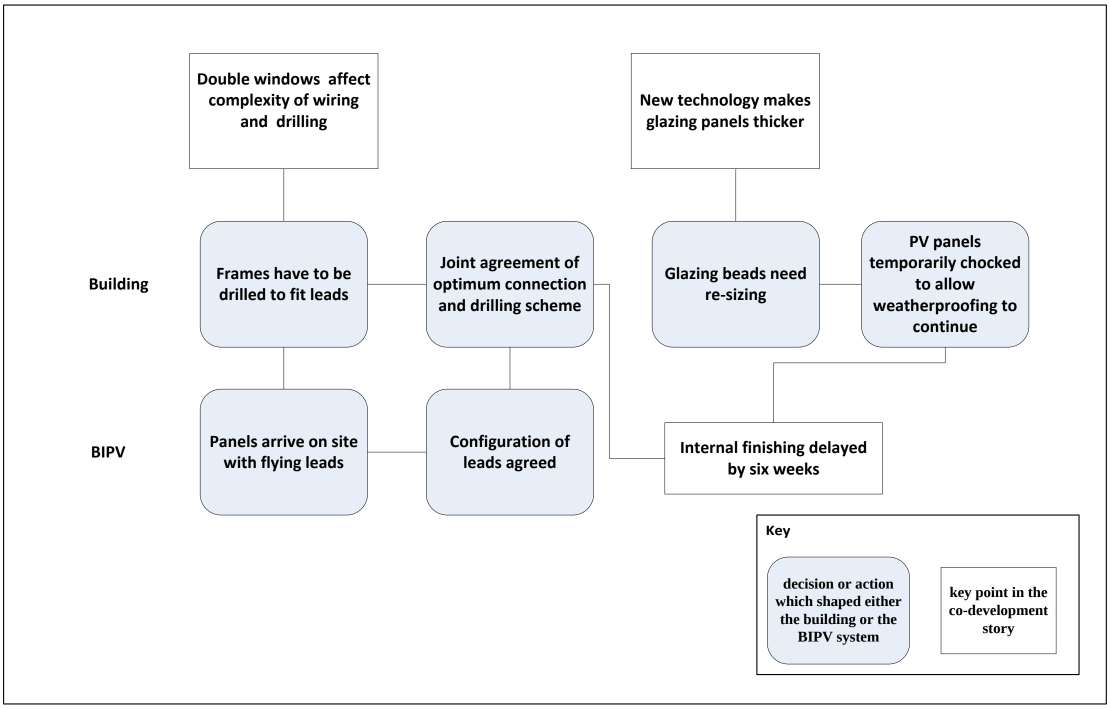


Figure 7-9: Co-development - mutual adjustment

This process of co-development by mutual adjustment led to some moments of unfolding innovation as the installation team developed new ways of integrating the frames and glazing into the building.

Homogeneity of appearance

The second series of co-development events relate to homogeneity of appearance of the BIPV and the building and are shown in Figure 7-10. At the initial stage of the project the decision to use BIPV in the windows dictated the choice of thin film technology. 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 and 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 very different 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 (NW) was unfamiliar with the differences in the two technologies but recognised that the monocrystalline cells would affect the external appearance of the windows and worked with the glazing supplier (WA) to optimise the layout of the cells and logo, allow an even border and symmetrical cell spacing.

The knock-on effect of this decision was that the changes to cell spacing affected both the generation potential of the technology and the aesthetics of the windows from the inside. Instead of a semi-transparent brown film, 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 glazing panels (resulting from the specification of thin film technology) would not apply when monocrystalline technology was used. This meant that the windows could have been specified as one panel, thus reducing the number of joins and flying leads.

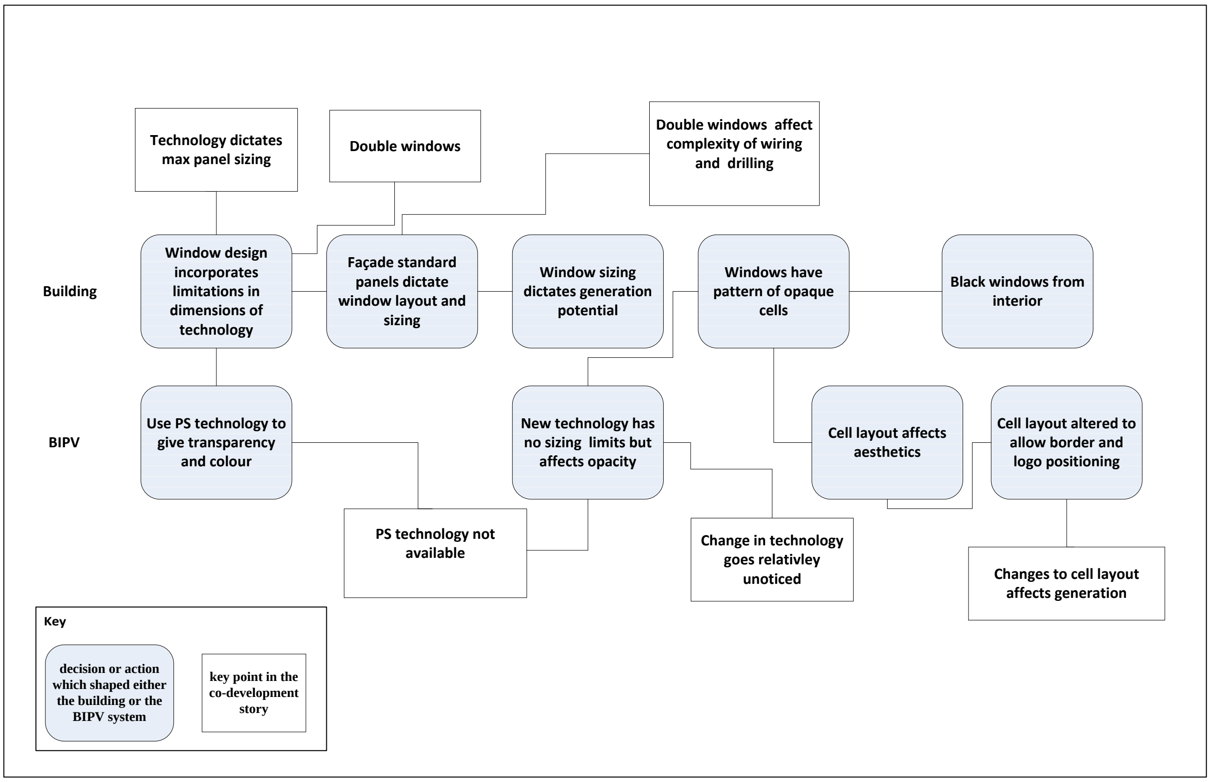


Figure 7-10: Co-development - homogeneity of appearance

This series of mutual articulations between the appearance of the BIPV system and the appearance of the building seemed minor to the project actors, but resulted in the sub-optimised generation potential of the system, delays and re-work, and a set of windows which were opaque. 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 potential further.

Procedures of working

As in the previous case study, an aspect of co-development occurred as a result of the procedures of working used during the project. During the pre-tender stage, the M&E design consultant (SAW) and architect (NW) developed the technical specifications and the main contractor decided 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 place all the other parts of the BIPV system into 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: 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.

The packages went out to tender and were duly awarded. The main contractor (TH) was not aware of the requirement for detail design of the system and the potential suppliers 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 (BSW) had neglected to design how the wiring was to run from the frames and had been unaware that the inverters needed to be ordered. Figure 7-11 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.

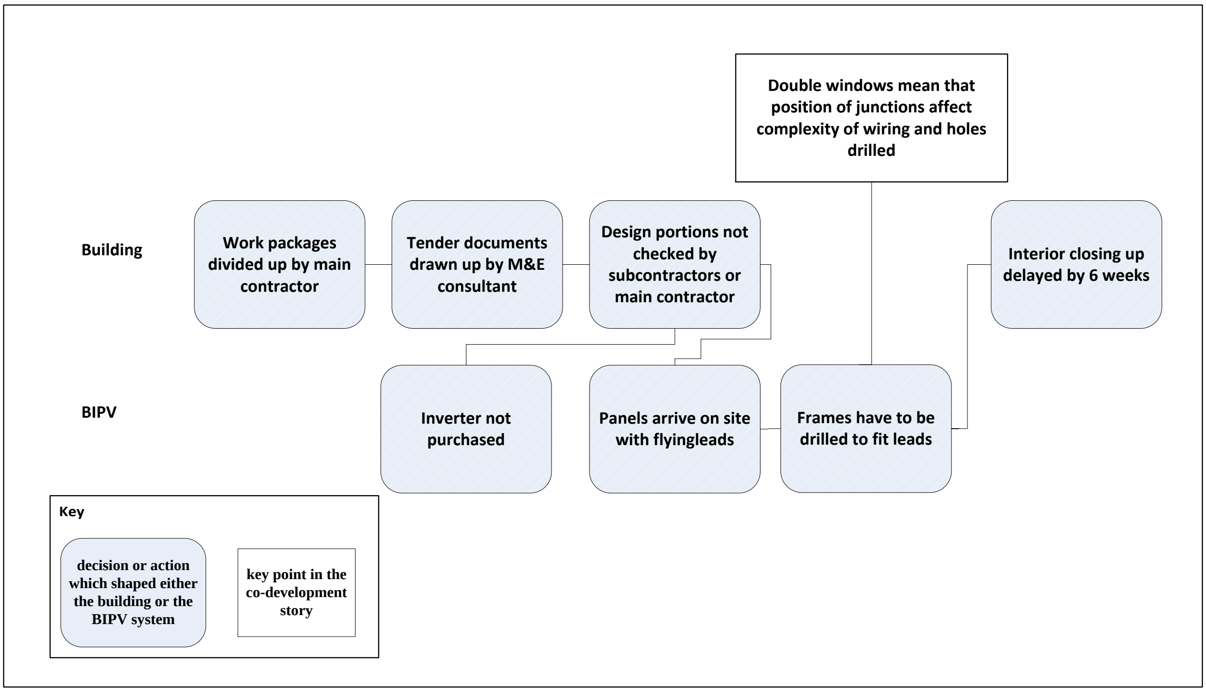


Figure 7-11: Co-development - procedures

In summary, the four examples of co-development in Future Green illustrate the three types of co-development identified in the previous case study (lock-in; interdependence of appearance; mutual adjustment and adaptation), together with examples of unfolding innovation as the BIPV was integrated within the building. These mechanisms and reflections of their importance on innovation are discussed in Chapter 9.

7.9 Issues about BIPV and the challenges which it poses for project teams

Several issues in this analysis have particular relevance for the construction sector: unfamiliarity with the technology; BIPV expertise; system considerations; the motive for including BIPV on the project; the role of social artefacts; and construction practices.

Unfamiliarity with the technology

Unfamiliarity of the project actors with the technology led to several unanticipated consequences which had profound implications on the subsequent direction of the project. Neither of the main contractors had previous experience of BIPV which meant that when they were placing the work packages for tender, they placed the BIPV into the envelope package. They were unaware that the envelope consultant had parcelled the electrical part of the BIPV into the electrical contractor package and had included a considerable design portion within the tender document. When the main contractor (TH) considered the electrical package tender bids, no attention was paid to the requirement for design of the BIPV electrical system, either by the main contractor or by the electrical contractor. This meant that there was no coordination of the whole BIPV system and that when the packages reached site there was confusion over how to wire up the cables, where to run the wires to, and who should have ordered the inverter.

> But the coordination and understanding the wiring and the schematics fell into nobody's package, because the PV was in the envelope guy's package, and BSW, who are doing all the M&E on the job, [were] bringing a few spurs to it and an inverter. In fact the inverters we completely missed, and went into nobody's package, because it had fallen in this gap in between the two. And RR, who are doing our envelope, have no experience in PV, so they didn't know to raise those questions with us.
>
> Main contractor (TH01)

This led to a six-week delay in finishing the interior for the south west elevation, as the wiring issues were resolved. The need to drill the glazing frames and cladding to allow the wires to penetrate the building also raised issues of airtightness targets for the EPC certification.

> That’s our vapour control layer. So everywhere these cables had to come through, we had to penetrate through. And given that we [had] an air permeability of three, which, well you probably know is quite a stringent target; any of those kind of penetrations were a real worry for us. So for every one of those [holes] we were frantically going back and having to patch the VCL around and make sure that that was all sealed.
>
> Main Contractor (TH01)

Expertise

In this project, in a similar way to Case study 1, there was no single source of expertise for the BIPV system. The electrical design engineer viewed the PV as a packaged system that would be procured as a whole system, whilst the mechanical design engineer thought that his colleague was providing the design specification.

> Because the PV tends to be a fairly packaged system…someone will provide a whole system and then we’ll have a box on the wall that we need to connect into; to a large extent, so the limit of my involvement might be I’m providing a 16 amp way on the main switchboard and providing a sub main cable that is suitably sized up to their controller; everything downstream of the controller will be the packaged contractor.
>
> M&E design consultant (SWA02)

> We’re the mechanical and electrical designers. So my electrical colleagues would have been fully aware of the requirements in terms of photovoltaics, and they may have incorporated their requirements onto a schematic diagram, as opposed to something that was more of an installation detail; the reason why we didn’t look at the installation detail is because we consider that to be outside of our remit.
>
> M&E design consultant (SAW01)

The façade supplier was clear that the wiring fell outside their remit although the main contractor was sure that the façade supplier had a plan for the installation.

> We let these wires come out so somebody else could wire them up. We don’t get involved in any of that, we purely put the window in and leave a tail for somebody else to come along, which is M&E.
>
> Façade supplier (RR01)

The PV laminate supplier advised about panel layouts, and tried to ensure that the architect was happy with the layout and that the connections within the panels were efficient, but did not get involved with the wiring or string configuration. The façade supplier assumed that the site M&E contractor would install the system (although no one had designed it) and the main contractor relied on the design engineers to have done the initial design. In this case, not only was there no single "go-to" expert, the project actors did not seek the expertise but relied on someone else to be the expert. This small quotation illustrates the belief that there is one person who will answer the questions, but similar to the "he" in case study 1, the "PV guys" in this extract do not exist.

> And I think again they were kind of coming to us and saying, we need the information off your PV guys.
>
> Main contractor (TH01)

System considerations

In this project the visible inclusion of BIPV was the key consideration - the architect was clear that the most important thing was for the panels to be seen. When the glazing supplier calculated that the generation potential would be severely reduced by the deep reveals on the windows, the architect was adamant that the design would stay as it was.

The change in technology from thin film to monocrystalline cells almost passed without comment or thought - they both provided the visual element for the building, but the effect of the change had a very large impact on the final aesthetics of the building. The frustration of this choice was articulated by the lettings manager.

> in terms of the specification which are these solid panels, that's a product which would never be specified now, because there are newer products which are transparent and

> basically preserve the view but still do a job, and one would imagine do a better job than these in terms of generating power.
>
> Lettings manager (FS01)

The project team focussed their attention on the visible element of the BIPV system (i.e. the glazing panels) and this focus led them to ignore electrical package. The main contractor illustrated this point when talking about the perception of BIPV.

> But essentially, the way those PV plans have been put in is they’re just into a double glazed system, so it’s just like installing a window. Actually installing it onsite is no different than just glazing a standard window.
>
> Main contractor (TH01)

Motive

The motive to include BIPV on the project was purely based on the desire to have a statement of sustainability as a selling feature on the building. This led to a focus on the architectural contribution that BIPV could make and a total disregard for its potential to generate electricity. This in turn led the architect to pay attention to the cell layout on the windows with a view to getting a regular pattern of cells with an even border around the windows, rather than trying to optimise how the connectors would fit within the façade.

In this case study there was very little consideration of the technological assemblage of the BIPV system - rather it was conflated with the glazing panels. At the detail design stage in the project the artefact of the glazing panel was sub-divided into glass, cells and connectors, but this was only done in discrete meetings, between architect and PV laminate supplier, or between the façade supplier and glazing supplier. The main contractor and M&E contractor were not part of this discussion and when the units came on site any agreed wiring configurations were changed to allow the units to be integrated into the façade. Even when the wiring work was done, this was not perceived to be related to the BIPV system - rather as an addition to the M&E contract. This lack of clarity over what exactly constituted the BIPV system gave rise to confusion over which actor was responsible for which part of the technology. For example the M&E contractor considered the BIPV element as a black box which had to be connected to the G59 panel, rather than realising that the inverter had to be sized and procured as part of the package.

Social artefacts

Social artefacts such as the project schedule, funding criteria and EPC criteria and contracts played an important part in shaping the co-development of the building and technology. The actors tend to defer to these artefacts as immutable truths rather than as tools which were developed to assist the smooth running of the project. These social artefacts significantly impacted the stabilisation and closure of problems and solutions.

This analysis reviews four main issues surrounding the adoption of BIPV in the building which were present throughout the project: lack of familiarity with the technology; the presence of a PV expert; the motive for the inclusion of BIPV; the effect of social artefacts. These four issues were present in the other case studies and will be discussed in greater depth in the Chapter 9.

Construction Practices

The three themes of contracts, continuity and collaboration, and change orders which were apparent in the first case study also run through this case study.

The way in which the work packages were divided was decided by the main contractor, but the content of each specified by the M&E pre-tender design engineers.

> In terms of the level of design that we are responsible for, we are responsible almost for the strategy and the performance requirements. In terms of the final installation details, that would be over to the M and E contractor and that is captured within the M and E preliminaries.
>
> M&E design consultant (SAW01)

The BIPV was considered by the main contractor to fall into the envelope work package and so the M&E design engineers' tender specification for the BIPV was developed in such a way that the façade (or envelope) package included the PV glazing and the M&E contract for internal fixings included the electrical portion of design for the PV system.

> The PV was quite difficult in the sense that because it was procured as part of the envelope package, it went into the envelope contractor design... Actually installing it onsite is no different than just glazing a standard window. So in that sense the installation onsite has been quite easy. …In fact the inverters we completely missed and it went into nobody's package, because it had fallen in this kind of gap in between the two.
>
> Main Contractor (TH01)

> We've done a specification sheet for the photovoltaics so we will have liaised with the manufacturer and with [the glazing supplier], extracted specification based on their advice, incorporated that into our specification and then the job goes out to tender. …And then [the main contractor] who ultimately were the successful contractor, they would have then employed [the M&E contractor], who would have taken our specification and implemented it. And I think there's a clause in our specification that suggests that 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 Contractor (SAW01)

The M&E design contractor had included a substantial design portion within the work packages, but the main contractor (who approved the tender packages and awarded the contracts) was not aware of this and did not check that that design work had been which had been done. This lack of continuity meant that the electrical element of the BIPV design was not done and the inverters were not ordered.

> So in that sense 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. But then all of the wiring, and what have you, just became all a bit of a, not a nightmare, I just don't think anybody really understood what we were installing until it landed onsite; and then we could actually physically see it and go, oh right, we've got cables coming out here, here, and here, and how are we going to connect all of these?
>
> Main contractor (TH01)

In this project there was a history of past collaboration between the façade supplier and the glazing supplier and the glazing supplier and the architect. In the case of the façade supplier this familiarity led to an assumption that the glazing supplier had prior knowledge about the technical specification of the job which in turn led to a lack of questioning and checking of drawings. These assumptions meant that neither party checked that the gaskets holding the PV panels in position were of the correct thickness, nor that the reveals in the window were of the correct size. The following quotation illustrates the closeness of the relationship.

> Well probably a starting point would probably be from when the tender comes into [the façade supplier], now that can sometimes come from maybe [the glazing supplier] have put us forward on a job, or told us about a job, and then we'll look into what's in the tender specification. And in this case there was the photovoltaic units, [so] we will then go back and ask [the glazing supplier] if they want involvement.
>
> Façade supplier (RR01)

Similarly, the ongoing relationship between the architect and glazing supplier meant that even when the glazing supplier could no longer offer the original specification of technology, the architect was inclined to stick with the glazing supplier and use inferior technology rather than choose to break with the glazing supplier to source better technology (thin film technology was available from other suppliers). The following quotations illustrate the closeness of the relationship and how this led to lock in of the technology.

> So then we basically took that forwards with [the glazing supplier] because obviously the curtain wall subcontractor who we use quite a lot now, they obviously have two systems, or they had two systems; the original system that we specified stopped as the job was going out to tender, so we had originally specified a different system but they had stopped doing it, so we had to move back to the normal PV.
>
> Architect (TH01)

> …we do a lot of work with NW over the years and this came out...
>
> Glazing supplier (WA01)

> And that's when I think it came about that you [glazing supplier] had already been in, or had been asked to go in, to speak to [the architect] about it before we were even involved…you'll find in [the architect] specification it's probably said that the job is a [glazing supplier] spec and the photovoltaic units; and probably because [glazing supplier] had involvement from day one, he knows about it, and he would be quite happy to just deal direct with WA to be honest.
>
> Façade supplier (RR01)

In this project the PV laminate supplier was clear that his quotation was based on a loose assessment of the probable generation potential of the panels (plus or minus ten percent). Changes in layout of the cells and header bars affect the efficiency of the panels, but often advancements in technology are used to keep the generation potential within the agreed margins. The panel supplier explained how the long span of a project makes the use of these advances in technology possible.

> Because what happens, what you have to remember all this happening over two or three years and the cell that we've quoted at the beginning is not the cell that's going to be installed at the end, because hopefully the technology is better.
>
> PV laminate supplier (LE01)

Changes to the location of the inverter also allowed the rather embarrassingly low generation output to be hidden rather than, as was first specified, displayed in the foyer of the building.

These examples of changes in design illustrate the positive contribution of change, rather than the negative one often portrayed.

These challenges for construction practices when new technology is introduced are common to all three case studies and are discussed in Chapter 9.

Chapter 8: Case Study - Synergy Court

This chapter presents the third and final case study, giving first a general description of the project and then breaking down the case study into five episodes: initial scheme; pre-tender and tender process; pre-contract design order; detail design; and installation. For each episode it provides a narrative account of what happened, focusing on the succession of problems and solutions, reflecting on the changing technological frames of the actors and exploring the co-development of the building and the BIPV. The chapter goes on to summarise the way that actors mobilised different frames at different times throughout the project, explore the mechanisms of co-development between the building and the technology, and finally summarises the issues and the challenges which the project team faced as BIPV was integrated within the project.

8.1 Description

Synergy Court is an interdisciplinary biomedical research centre which was designed to serve a medical research partnership between three national research organisations and three universities. It is located at the junction of three neighbourhoods: a grade 1 listed (1967) railway station built in 1868, a grade 1 listed (2015) public library built in 1999 and a community of council housing and schools. This mixed neighbourhood made the council very sensitive about the design, and as a result the process of gaining planning consent was long, requiring extensive community and planning authority engagement. Project planning began in 2001, with a first architectural practice submitting several plans for planning consent which were rejected by the council. A second architectural practice was appointed in 2005 and new plans were submitted in April 2008. Planning permission was granted in December

2010. Ground works began in April 2011 and the building was “topped out” in June 2013 with an estimated completion date of early 2016. The project used a Design and Build contract.

The building has a curved roof which conceals the heating and cooling units and incorporates photovoltaic fins on the south elevation. In addition to the photovoltaic panels the building uses a combined heat and power plant to reduce carbon dioxide emissions. Large cantilevered bay windows and tall glass atria increase natural lighting and water efficient fittings reduce water consumption. One third of the building is below ground level to minimise its visual impact. The laboratories are arranged over four floors, each floor having four interconnected blocks to encourage researchers from different fields to collaborate. The laboratories are designed to be adaptable to change as new scientific opportunities emerge in the future.

Ten interviews with members of the project team were conducted over a sixteen month period, starting just as installation of the PV louvres had begun and finishing just before commissioning of the BIPV system. Chapter 5 (Methods) gives detailed information about those interviewed. In the following analysis interviewees are referenced by the firm they represent: architect (SL); main contractor (BP); M&E design consultant (FS); louvre supplier (FD); electrical contractor (CAT); and PV laminate supplier (LE). A number is added to the reference as a unique identifier for each actor in the firm. For example: “louvre supplier (FD01)” represents the louvre supplier firm - FD, and is the first actor interviewed from that firm. “Louvre supplier (FD02)” indicates the second person interviewed at the louvre supplier firm, and so on.

8.2 Episode 1: the initial Scheme

The first episode covers the development of the concept design for the building to the point that of initial design, where both the outline of the building and the configuration of the BIPV system had been defined.

8.2.1 **Episode 1: narrative account**

In 2001 the client (a collaborative research charity) commissioned an architectural practice (Anglia) to develop plans for a new collaborative research space for the research partners. The client brief was for a building of four interconnected towers which would encourage collaboration. The architect (SL) described the client vision as follows:

> The client body saw science moving...to be a lot more collaborative...they looked back and all their best innovations, all their real breakthrough moments were when people had chance encounters and met each other…So the idea was that there were four main blocks to the building and that within that there was a big atrium space and that atrium space helped to draw people in, …they really wanted to show that science is now something that's very much at the forefront in this country, that it's something we're very good at. But they want a more public face. Science buildings are normally, historically aren't pretty…they're in basements and they're very formal and the idea was that the institute is more of an outreaching building, that they want public engagement, that they want people to see what they're doing.
>
> Architect (SL01)

The project is located in a London borough and was subject to the London Plan Part L renewables contribution (commonly referred to as the Merton Rule). Briefly, the Merton Rule (developed by Merton Council in 2003) required new developments above a threshold of 1,000 square metres that could incorporate on-site renewable energy production equipment to generate at least 10% of their energy needs (Merton Council 2015). As the research centre would use considerable amounts of electricity to carry out its research, the figure of 10% was felt to be unrealistic by the client and so negotiation took place between the Council and the clients and architect, to agree a more realistic figure of 1% for renewable energy generation.

> With this base electricity demand…we demonstrated that we couldn't feasibly meet [the 10%]…So within the planning documentation, it's a commitment for 1%.
>
> M&E consultant (FS01)

Within the four-tower design, the architects included a combined heat and power plant, PV roof mounted panels and integrated BIPV in the cladding of the upper floors of the south elevation, and submitted plans accordingly. The council did not feel that the building design fitted into the architecturally sensitive area and over the next four years refused planning permission. The client engaged a second architectural practice (SL) to rethink the design and develop a scheme that would be acceptable to the council. As the second architect (SL) explained:

> This particular one was a sensitive location with the relationship to listed buildings, very large institutional type libraries, a station, and then a much lower scale residential feel. And trying to balance how a building of this scale would sit within an urban context of that nature was [challenging].
>
> Architect (SL01)

The architect (SL) then went on to describe how the original plan was altered to create the final design of two curved roof wings of different heights which covered the four towers. These curved wings were made from ribs of louvered fins, which created an architectural balance with the nearby station. The purpose of the curved roof was not just as an architectural device to allow the building to fit in with the surroundings, but also a way to hide the air handling plant at roof level.

> …the building has an awful lot of plant...there's five times more air handling kit and electrical kit than you'd normally expect in an office building of this size, so it's a huge challenge to try and encapsulate that in a building form that is seductive …so we came up with this curved roof form which actually also mirrors the old railway.
>
> Architect (SL01)

As the new architectural team developed the plans for the building, it became clear that although the council were very much in favour of the new design, they were intent on keeping the initially agreed generation figure.

> That number that the array had to give out then became almost set in stone…so it already had a target it had to meet, which at the time was Part L 2010…so when we came on board we knew we had to hit a certain output and to get to that output we had to prove that we could incorporate that many PVs.
>
> Architect (SL01)

This caused a series of iterations in the design, as the architect (SL) and M&E consultants (FS) endeavoured achieve the agreed PV generation figures with the new design of the building. The location of the building, the reduced massing and the new curved roof shape made it difficult to incorporate BIPV into the building façade.

> There was a debate about whether they should be incorporated in these, in the main claddings…We felt that was probably not the most appropriate place for them because we have lots of shading on the south side.
>
> Architect (SL01)

The challenge of achieving the generation target with the curved design was highlighted by the M&E consultant (FS) as he spoke about the issue of incorporating PV cells into the curved fins and the shading issues that were involved.

> One of the things we did, were quite wary of was over-shading because of the design…the architects did quite a lot of rendering to make sure, so it actually fed back into the design of the panels because they are 750mm wide, but we only used the front 650mm for the actual active area to avoid the over shading.
>
> M&E consultant (FS01)

As part of the original outline design - before the second architect joined the project - a room had been set aside in the roof to house the BIPV inverters.

> [When] we joined this project at a midpoint there was already identified a place where the inverter room was going to be. It had to be somewhere on the roof and…how all the wiring goes back to that was already fairly well known and well understood.
>
> Architect (SL01)

The negotiations over the new design and the percentage generation figure took over two years and at the end of 2010 planning permission was granted. The an agreed revised renewable energy target was 221MWh of electricity, which was a little less than 1% of the predicted energy use of the building.

8.2.2 **Episode 1: technological frames**

As in the previous two case studies, this section illustrates how the actors viewed the technology through different frames through this episode and how tensions developed between the groups over conflicting goals. Figure 8-1 shows how the network of actors, technological frames, problems and solutions played out during the initial design episode and the following description draws attention to the main highlights of the episode.

The technological frame of Design Aesthete was evident at the start of the project when the planning officer demanded a building to fit in with the surrounding environment, and the second architectural practice (SL) was engaged to carry out this instruction. Similarly, the frame of User was mobilised at the start of the project when the client was intent on creating a space which would encourage collaboration between scientists, and insisted on some arrangement of four interconnected buildings. The client also wanted to engage the public with an accessible building which invited interaction. These aims were more important than the desire for a show-stopping design. It is clear that the first architect understood the client's User frame and worked with it to come up with the initial design, but that the second architect (SL) also understood the planner's frame of Design Aesthete and worked to incorporate the requirements from the User frame, the Design Aesthete frame and the Green Guardian frame into the successful design.

The Green Guardian frame was evidenced by the planning officer's insistence that the building generate 1% of its energy consumption through renewable technologies. The M&E consultant (FS) and architect (SL) began to see the technology through the frame of Generation Maximiser, as they started to calculate the generation output from the curved roof and take shading of the panels into account. Tension between the frames of the Design Aesthete and the Green Guardian in terms of their goals surfaced when the main goal of the Design Aesthete was the fit with the local environment, while the Green Guardian frame was focussed on the need for renewable energy. The two frames became aligned when an outline scheme included BIPV in the curved roof louvres, but as the Green Guardian requirement to maintain agreed generation output remained unchanged, tension increased between these two groups. It was only when the problem was seen through the Generation Maximiser frame that the actors could share a focus for these concerns.

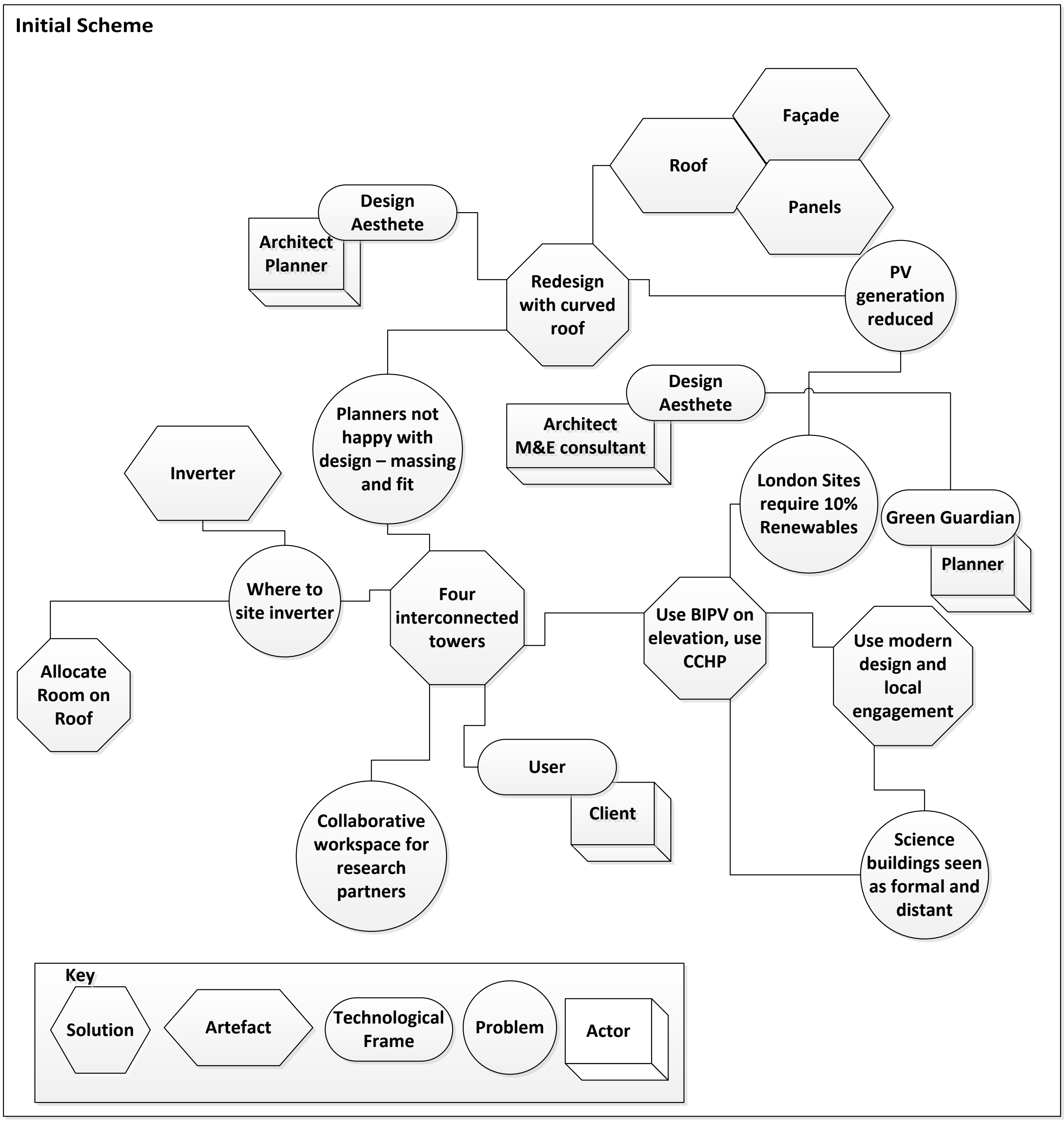


Figure 8-1: Technological frames mobilized in episode 1 (initial scheme), Synergy Court

The analysis above illustrates how the technological frames of Green Guardian, User, Design Aesthete and Generation Maximiser were all mobilised by the actors during this episode, and how many of the actors related to the technology through more than one frame. This shows how conflicting goals between actors using different frames gave rise to problems and how solutions were developed through different mechanisms - re-alignment of frames (the new design satisfying both the aesthetic requirement and the energy generation requirement), the establishment of a particular frame as dominant (the need to maximise generation) and the disappearance of a frame when the requirement has been satisfied (client removes the user frame from the episode once the requirement for interactions between researchers had been met).

8.2.3 Episode 1: co-development

This first episode illustrates how rather than the BIPV or the building being fixed, the BIPV system accommodated the building and vice versa. The summary of co-development during the whole case study is given in section 7.8.2, but two important elements of the co-development of building and technology occurred in this episode of the project.

i. The initial four tower design for the building and the Part L requirement for renewable energy generation led to the design of a roof and façade mounted BIPV system of a particular generation capacity.
ii. The rejection of the building design and the development of the rounded winged roof changed the configuration of the BIPV to include it in the roof louvres and reduced the available generation potential.

8.3 Episode 2: pre-tender design and tender

The second episode follows the development of the detailed system and building design and begins at the point where the curved roof design was detailed.

8.3.1 Episode 2: narrative account

The roof shape was designed using parametric modelling and the position of the PV louvres was fixed based on that design.

> We used parametric modelling…actually the roof, whilst it looks complicated, in its nature is relatively simple. It's a continuous arc that is then pitched in section, and from that we developed the series of parameters that helped us to inform where the louvres on the roof go, and in turn where the PVs could be installed.
>
> Architect (SL01)

In order to meet the 1% generation target, the architect (SL) and M&E design consultant (FS) had to optimise the azimuth (angle) of each PV fin in the roof. This was achieved using an algorithm developed by the architect's firm which maximized the achievable output of electricity.

> [We] essentially wrote a script that allowed us to tweak any point of the roof and it… allowed us to test a lot of options and …develop a scheduling of where the PVs could go, how much area we were getting, what the relative angles were...it was such a form, part of the form of the building, [that] we had to give the engineers the exact angles of everything, and what way they were facing, because from that they were then able to calculate the output from the array.
>
> Architect (SL01)

The architect (SL) and M&E design consultant (FS) agreed the final layout of the PV roof fins and the resultant generation figure. This generation output was used as the basis of the revised planning submission. At this point the layout and generation figures were locked into the design.

> So at that point the actual, the planning condition was written around: you have to produce this amount of power from that array.
>
> Architect (SL01)

Once the outline design had been completed, the main contractor (BP) was appointed by the client and took responsibility for dividing the project into tender work packages. The M&E design contractor (FS) designed and outline PV package which included the calculated fin lengths and angles, standard monocrystalline technology and a conventional string arrangement, to generate 221 MWh of electricity.

> We were looking at it as a standard stringed system with two, three, four, twenty, I can't remember how many inverters, but as it was being looked at, at the time, as a stringed system.
>
> Louvre supplier (FD03)

The M&E design contractor (FS) included the BIPV element of the design (including the bracketry system to hold the PV fins at the required angles) in the general roof louvre work package and allocated the electrical portion of the BIPV system to the general electrical work package. Five firms were invited to tender for the roof louvre package. One louvre supplier (FD) read the work package and became concerned that the required generation figures could not be met by the standard arrangement indicated in the work package. The louvre supplier (FD) used different computer packages to calculate the likely output from the PV fins and it became clear that there was a mismatch in standard data used. The M&E designer consultant (FS) summarised the difference by alluding to differences in the unit of measurement:

> So it's a kilowatt hour requirement for the PV array, but with FD and LE, what they work to is a peak design, so they were unwilling to commit to a kilowatt hour per year because [it's] based on weather data from an idealised year. So depending on what the weather conditions were for the year you may or may not hit the target…Also we'd used a certain software tool to work out what it [the PV] could produce, and they were using an alternative tool and …they do give you quite a different result, so there was a bit of to-ing and fro-ing, …
>
> M&E design consultant (FS02)

The louvre supplier (FD) attributed the difference between the tender figures and their calculated output to several things: the input data in terms of global position and azimuth; the efficiency of cell output once laminated into glass; and the weather data used. The eventual louvre supplier (FD) calculated that the maximum achievable output with the arrangement specified would be 188MWh (in contrast to the 221MWh calculated by the M&E design consultant (FS).

> We started looking at how do you calculate it, and...on the market there's various tools available for calculating PV outputs, [but] the weather data they use, changes from one to the next, ..and that can change the output you predict by 5 or 10%,…how does anyone know what you're actually going to get, it's complete guesswork; and I calculated it on 4 different systems, …they said the minimum efficiency is 15%, cell efficiency; or power efficiency is calculated on the area of the cells against the area of the panel,…but actually because it's laminated and various module efficiencies [this] reduces the actual output to 12%."
>
> Louvre supplier (FD04)

Over a period of four months the louvre supplier (FS) produced ten documents showing what they felt could be achieved and reported back to the main contractor (BP) that the required output could not be achieved using the arrangement in the specification. This view was supported by the three other tender firms - the fifth firm declined to quote.

During this period the louvre supplier (FD) had extensive discussions with the PV laminate supplier (LE) who made several suggestions about how the system could be improved to increase generation potential. The PV laminate supplier (LE) suggested that the louvre supplier (FD) specify a new technology cell - the "Q" Cell - and use micro inverters on each PV louvre, rather than the more conventional standard inverters.

> During the process, we told him what the problems were, we told him what we want to do - which was basically get 20% more…And we said, you're the specialists in PVs, how can we improve?...and he pointed us to a Cambridge start-up company…and we worked with them, to come up with a solution using micro-inverters.
>
> Louvre supplier (FD03)

The louvre supplier (FD) had discussions with the main contractor (BP) and design contractor (FS) and suggested that rather than using the specified system, the BIPV specification be changed to allow new Q cell technology and micro-inverters, which would increase the achievable generation to just below 200MWh. The louvre supplier insisted that significant pre-contract design would have to take place before a suitable system could be specified.

The main contractor (BP) was very reluctant to accept the change in specification and the louvre supplier (FD) had to work hard to convince the main contractor to listen.

> We had [M&E consultant] occasionally, it was mainly done through [main contractor], ourselves, we had people like [PV laminate supplier] came down, because there was almost an unwillingness, from some parties, to listen to what we were saying, even though we had carried out two or three other PV projects previously, this was the first time with micro-inverters and we had to bring in a number of specialists.
>
> Louvre supplier (FD03)

The main contractor (BP) accepted what they said, but asked all the companies to quote based on the original arrangement so that the quotations could be compared. The suppliers complied with this request, but entered caveats in the tender document to indicate that the generation figures would not be achieved.

In response to the problem of achieving only 188MWh of the specified required output of 221MWh, the main contractor called a tender meeting to discuss the issue. At the tender meeting the louvre supplier (FD) presented the micro inverter system and suggested that the main contractor (BP) and architect (SL) accept a change to the design and use micro inverters as a way to achieve the required output. The concept was presented to highlight advantages in efficiency, buildability and safety.

> We made the decision - this is the best way for us to present it as a package…it's a system that maximises the output of every single panel, the wiring actually is simpler, because when you're on normal PVs, you're working at very low voltage and high currents, which is very dangerous, so [if you] put it straight back to 240 volt everywhere, so it's normal building wiring, no special requirements for it, that simplifies that…Because of the structure, we could just wire down each hoop to a collection point at the bottom, and then along the building in a very simple manner, and for the electrician's involved, it's just for them mains voltage; OK it's quite large, but it's nothing compared to some of the cable sizes in the rest of the building for the supply of the building, and it just seemed to us the most logical way to do it. So that's what we presented at our tender in our package.
>
> Louvre supplier (FD04)

The architect (SL) saw that this was largely a positive change:

> There was a very interesting shift when we went to tender in that FD wanted to use the micro inverters, which was I think a good move in the end because it meant that they were far more tune-able and if you lost one you didn't lose a whole array. It saved a whole room.
>
> Architect (SL01)

The main contractor (BP) accepted that generating the required amount of electricity would not be achieved by conventional inverter string configuration and decided to award a pre-construction service agreement (PCSA) to the louvre supplier (FD) so that a system using micro-inverters could be designed. The main contractor (BP) understood that the cost of the new system would be higher than the conventional one, but agreed to the new design because of the need to achieve the target generation figures. The main contractor was insistent that the generation potential of the new system should exceed 200MWh. The louvre supplier (FD) summed up the situation:

> We were saying, and everybody was saying, you can't achieve it. So it obviously had an effect on FS's, what they'd put forward, and so we've said that you would need to do more work. If we want to increase it, we'd need to do some big studies and a lot more work. The long and short of it was, we secured PCSA.
>
> Louvre supplier (FD03)

This episode concluded with a pre-contract design order (PCSA) being awarded to the louvre supplier so that the BIPV design using micro inverters could be detailed.

8.3.2 Episode 2: technological frames

The following analysis illustrates how tensions between actors in different technological frames led to conflicts between the groups during this episode. Figure 8-2 shows how the network of actors, technological frames, problems and solutions played out during the pre-tender and tender design episode and the following description presents the main highlights of the episode.

Once the project team had understood the importance of optimising PV generation, the Generation Maximiser frame was very evident at the start of the episode. This is illustrated when the architect (SL) and M&E consultant (FS) developed new software to optimise the angles of the roof, and also as the companies tendering for the BIPV contract tried to fulfil the generation required in the tender documents. The Council's planning officer mobilised the Green Guardian frame by maintaining the requirement for the 1% generation figure. As the work packages were defined for tender, the main contractor (BP) identified with the Cost Watcher frame. Once the tender documents were released, two frames - the Design Optimiser frame and the Generation Maximiser frame - dominated the way that the actors related to the technology. Frequent conversations with the PV laminate supplier (LE) were used to improve elements of the design and to check cell spacing and borders to maximise generation. Towards the end of the episode many of the actors mobilised the Generation Maximiser frame, as the louvre supplier's (FD) calculations showed that the tender design could not yield sufficient generation and that an alternative would be necessary. Initial actors sharing this frame were the louvre supplier (FD) and PV laminate supplier (LE), but they were joined by the main contractor (BP) and the M&E consultant (FS) as the gravity of the situation was brought to their attention. The louvre supplier (FD) adopted the Risk Minimiser frame by refusing to guarantee the generation figure required in the tender document. It is interesting to note that the tender document itself (in the form of a contract) played an important part in making clear the potential risks of not meeting the contract requirements.

Tensions between actors sharing a frame occurred when both the M&E consultant (FS) and the louvre supplier (FD) within the Generation Maximiser frame disagreed over the method of calculating the generation potential of the system. Both actors were focussed on maximising the output from the system, but were in disagreement about the methods to be used in the calculation, although their objectives and attitudes to the technology were similar. The architect (SL) was invested in the model that had been written specifically for the project, whilst the louvre supplier (FD) used a tried and tested commercially available package and outlined problems with the weather data and efficiencies used by the architect and M&E design consultants.

As in episode one, there were times when actors from one frame began to see the technology through other frames and could then present their ideas in such a way that the idea became acceptable to those already using the other frames. An example of this is when the louvre supplier (FD) offered a system of micro-inverters at the tender meeting with the main contractor (BP) and M&E contractor (FS). The louvre supplier (FD) was part of the Generation Maximiser group, but understood that the main contractor was interested in buildability and site safety which fitted within the Design Optimiser frame. He consequently presented the solution in such a way that the main contractor (BP) could accept it.

The analysis above illustrates how with the exception of Design Aesthete and User, all of the technological frames were mobilised by the actors during this episode, and how many of the actors related to the technology through more than one frame. The use of technological frames has again shown how conflicting goals between actors using different frames gave rise to problems and how solutions were developed through different mechanisms. This episode also shows that problems can arise between actors using the same frame, for example, the louvre supplier and M&E contractor using different programmes to calculate generation potential.

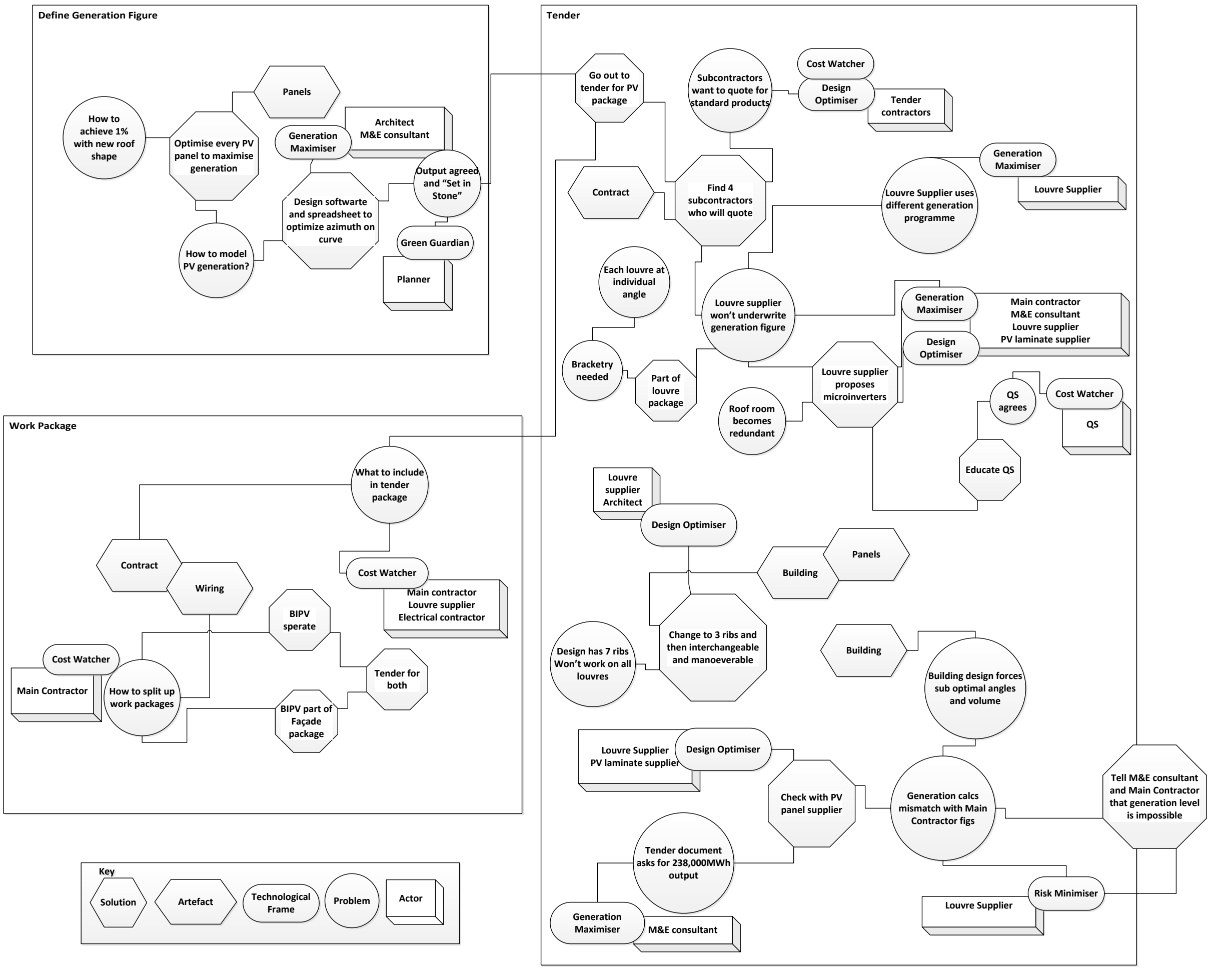


Figure 8-2: Technological frames mobilized in episode 2 (tender), Synergy Court

8.3.3 Episode 2: co-development

During this episode of the project, one major and one minor element of co-development between the building and the BIPV system were apparent.

i. The inclusion of a curved roof reduced the PV generation potential of the initial system. Rather than adopting a standard configuration of strings of PV louvres connected to a series of inverters, the new system developed by the louvre supplier used individual inverters on each PV louvre which fed to a series of AC combiner boxes and then to a distribution panel. This change had knock-on effects for the building in terms of wiring and cabling changes, which resulted in the need for more containment and bracketry, as well as changes to the energy management system.
ii. The room initially allocated for the inverters became redundant and the cost and complexity of the roof work package increased.

8.4 Episode 3: pre-contract design

This episode covers the period of the pre-contract service agreement (PCSA) awarded to the louvre supplier to design and cost a system using micro-inverters prior to a contract for the BIPV system being awarded.

8.4.1 Episode 3: narrative account

The PCSA was put in place in January 2012 with a remit to develop a detailed design of the new BIPV system. The scope was described by the louvre supplier:

> We worked under a pre-contract service agreement, whereby we had to come up with, effectively, the full design of the louvres, the system, method statements, finalised the output that we were still going to be estimating, and a final cost for doing the project in a certain programme.
>
> Louvre supplier (FD03)

The louvre supplier (FD) used the tender roof layout as the basis for the design and carried out detailed design around this.

> As far as we were concerned, the roof design had effectively been pretty much cast in stone. The number of louvres, the type of louvres in the various positions, all of that had been, not the design of them, but the type that they wanted there, were listed out…so we knew what we were bidding for.
>
> Louvre supplier (FD04)

The buildability of the design was revisited by the louvre supplier (FD) who altered the rib design supporting the roof fins, but had to maintain the complex individual orientation and sizing of each louvre.

> We effectively rationalised it to what we thought was a buildable, simple design. A cost effective design and a simple design that worked for the whole system…the architect's got five ribs on a louvre, in fact seven ribs on a louvre, we changed it to three, it will simplify the design and making that work for all types of louvres [is important] because every louvre's a different length, mathematically…and every louvre has a different orientation to the sun, which is where, probably the biggest challenge came for us.
>
> Louvre supplier (FD04)

To increase the generation, the PV laminate supplier (LE) suggested that the PV cells be specified as square in shape rather than the more conventional hexagon. This would be more expensive, but would increase the area and so the generation potential of each cell.

> We had to find a better cell, which was I think called a Q cell…most cells are, hexagonal or octagonal, we've got full square cells, to increase the output of the area They were more expensive, but the additional output was something like 4 watts, to 4.43 watts it was about a 10% increase but …we needed everything that we could get.
>
> Louvre supplier (FD03)

The PCSA package included design of the wiring from the micro inverters to the distribution panels. The outputs from each louvre micro inverter had to be wired to reach the distribution panel, from where it could be delivered to the main building supply system. There were 427 micro inverters in the system and rather than running each wire from the micro inverter to the distribution panel, the louvre supplier (FD) designed a system where the micro inverters were divided into 2 vertical streams, one for each side of the elevation. The wires from each micro-inverter were connected to junction boxes (in groups of 4) and from there to a series of combiner boxes (20 in total). These boxes provided a means of electrical isolation for each louvre and collected the output from the connected inverters. From here the output from the combiner boxes were collected into two cables and thence to two distribution panels. The main contractor described the system as follows:

> On one blade [louvre] of 6m you've got the micro inverter [at] one end, one at the other end, then we've got a central point, we're bringing the wiring down, so we've got the containment in It's a plug and play system, just plug them in and join them up and down to your universal, into the junction boxes, and bring it down the beam to a combiner box at the bottom on each hoop steel; and they in turn have got 12 this side and 8 the other, and the 12 will go to a central inverter room to one cabinet, and the 8 on the other side will come back to the other cabinet.
>
> Main Contractor (PB02)

The louvre supplier (FD) described how the work was to be divided between themselves and the electrical contractor (CAT).

> We did everything from the module, the inverter down to the AC isolator, we provided the AC isolator [and] the distribution boxes, but CAT did the wiring between them.
>
> Louvre supplier (FD03)

In addition to the wiring system, the louvre supplier (FD) had to consider the energy monitoring system (EMS) - both in terms of measuring the PV output and in terms of monitoring the condition of the 427 micro inverters. One of the unanticipated benefits from using micro inverters was that the micro inverter supplier was keen to develop a web monitoring system and this innovation was included in the specification.

> "The other beauty about the micro-inverters was it had its own reporting system, which was all wirelessly done, and you can monitor pretty much what every module is doing, at any time of the day, you can build that up over time … It gives you historical data and it also is pretty good for fault finding. If one head was faulty, and one was cracked, broken, wasn't generating, it didn't affect any of the other modules around it. …So it had a lot of serious plus points, the downside, if there is, if we can call it a downside, it obviously involves more inverters and more cost."
>
> Louvre supplier (FD04)

The use of micro inverters improved the system efficiency by reducing losses from wiring because losses from AC wires are smaller than those from DC wires. This advantage helped to boost the final generation figure from 188MWh to 204MWh.

> The figures were conservative, we're basing it on the lowest cable losses. You've got a cable that's, in some cases, going from the whole way down here all the way back to here, it's hundreds of metres long…that was also one of the benefits of inverting it here, that you get much less loss…you minimise the losses with AC.
>
> Louvre supplier (FD03)

By the end of the PCSA the louvre supplier (FD) had produced a design specification for the system which they were happy to guarantee. The new system increased the cost of the BIPV from £1m to £1.25m. The more difficult issue to resolve was the gap between the initial specified figure of 221MWh agreed with the local planning authority and the revised figure of 204MWh guaranteed by the louvre supplier. After negotiation with the planning office and because the revised figure was within 10% of the original figure the planners agreed the lower generation target and the main contractor agreed the change in specification and increase in project cost of the BIPV system. The louvre supplier (FD) confirmed that it was the shortfall in generation potential rather than the increase in cost which caused most concern.

> I would say the item that took the longest to resolve, and people to accept, was that it was going to be a reduced output, we managed, with micro-inverters ...to get it up to 204, but we …still said, that was an estimated output because there are so many variables.
>
> Louvre supplier (FD03)

Once the specification and design for the BIPV was agreed, the contract was issued to the louvre supplier on the basis of a turn-key operation in the second quarter of 2012. The louvre supplier (FD) viewed the BIPV system in the same light as supplying a motorised louvre system and so wanted to supply it as a complete system rather than as component parts. This gave the louvre supplier control over the final generation figures and gave the client a single point of contact for all enquiries. The approach was unique to the louvre supplier and differentiated them from other BIPV suppliers.

> In general we want to do a turn-key where we provide the louvres, the PVs, the inverters, the cabling all the way back to the inverters, and the final connection would be by somebody who is really qualified to make that mains connection. Because it gives the client one company to talk to if there is an issue afterwards. With a façade contractor, it would be, well, we only did that, we can’t be responsible for any issues. And then anybody who did the wiring or the inverting on that would be saying, oh it’s nothing to do with me, we just did the wiring. A turn-key operation, it gives the client a contractor, everybody some comfort in knowing that there’s one company to go and speak to… We see it as a bit of a niche. Other people don’t want to do it, we’re very happy to do it, we have the skills to do it, we have the experience.
>
> Louvre supplier (FD03)

8.4.2 **Episode 3: technological frames**

In this episode the Design Aesthete frame did not appear and the Green Guardian frame was subsumed into the Generation Maximiser frame. The other technological frames (Design Optimiser, Generation Maximise, Cost Watcher, Time Sentry and Risk Minimiser) were mobilised by the actors; tensions between them surfaced at a number of points (Figure 8-3).

The main contractor (BP), louvre supplier (FD) and PV laminate supplier (LE) viewed the technology through the Generation Maximiser frame, to work through a solution to achieve the required generation level. Although the maximum achievable generation figure calculated by the louvre supplier fell below the required 1% figure, the main contractor saw that without major cost implications and redesign (Cost Watcher frame), the limit of generation had been achieved. The planner recognised that the design was within 10% of the target and that this was unlikely to be improved without revisiting the design, and therefore approved the revised generation level.

Once the revised generation figure had been agreed, the social artefact of the contract became important and actors mobilised different frames in their response. To minimise the risk of not achieving the generation figure, and to improve chances of gaining a competitive advantage in winning the contract, the louvre supplier (FD) saw the contract through the frame of Risk Minimiser and proposed a turn-key contract for the BIPV system, something that the main contractor (BP) had not anticipated. This had a knock-on effect on the electrical contractor (CAT) who stood to lose part of the anticipated contract content (Cost Watcher). All three of the actors were keen to finish the PCSA episode of the project and proceed to the awarding of contracts and the start of detail design (Time Sentry frame). The Design Optimiser frame, which was not particularly mobilised in the first episode, was used in this episode as illustrated by the louvre supplier developing the web-based EMS reporting system with the micro inverter supplier.

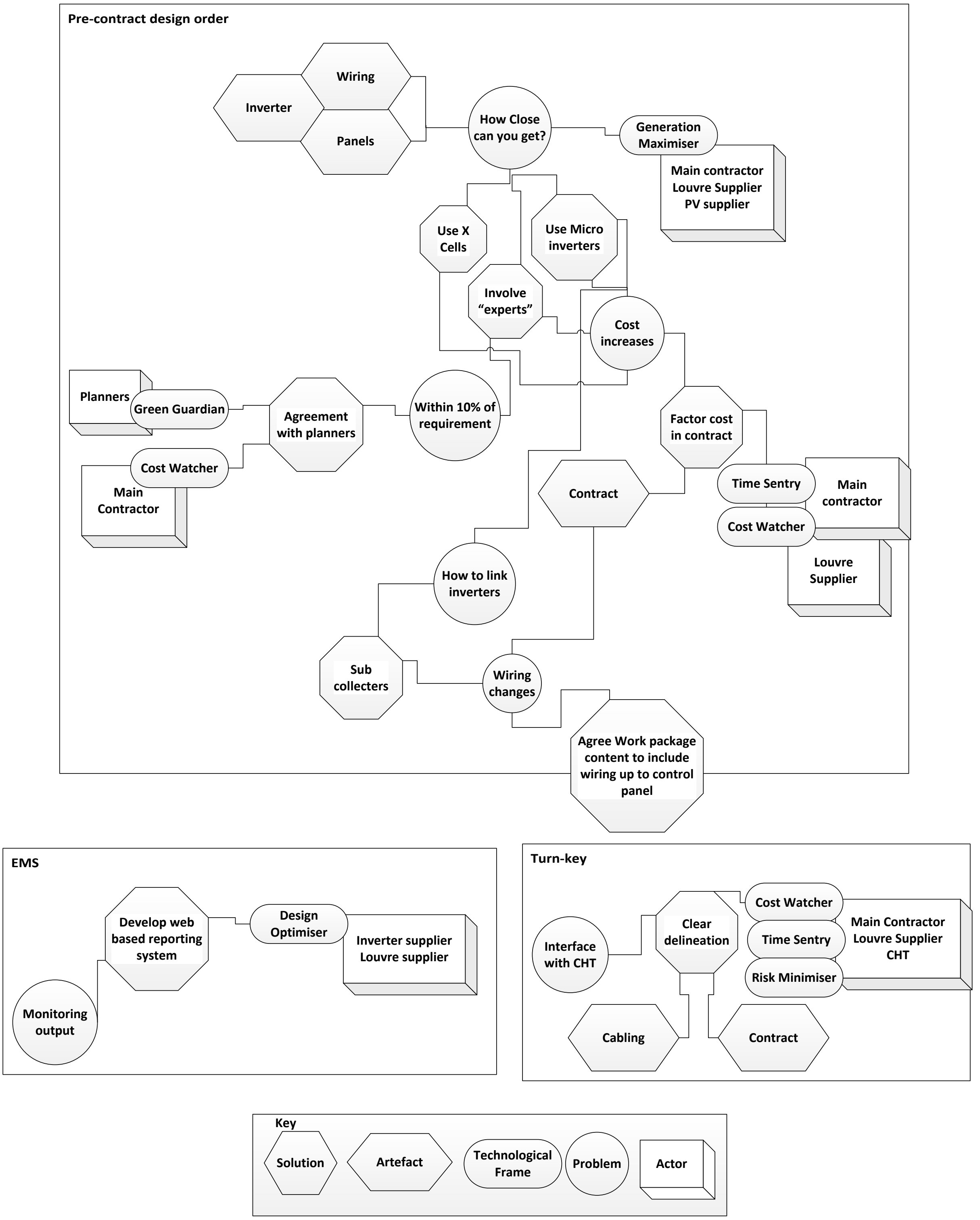


Figure 8-3: Technological frames mobilized in episode 3 (PCSA), Synergy Court

In this episode the need to maximise generation (Generation Maximiser frame) continued to dominate the problem solving, and the Risk Minimiser frame drove the louvre supplier to offer an innovative turn-key contract to the main contractor. In addition to tension between actors mobilising different frames to achieve different goals, tension between the actors also came from the presence of the contract as a social artefact which represented and reinforced the Generation Maximiser frame.

8.4.3 Episode 3: co-development

Three instances of co-development occurred in this episode of the project.

i. The louvre supplier rationalised the louvre design so that all the louvres had three ribs rather than seven. This made the manufacturing process simpler, and meant that the BIPV louvres had to be constructed this way too.
ii. The EMS system for the building had to be changed to accommodate the web monitoring system for the micro-inverters.
iii. The least visible but arguably the most important element of co-development story occurred when the contracts were awarded. Rather than the usual division of work packages along electrical and mechanical lines, the louvre supplier forced a turn-key solution for the BIPV contract. This changed the way that the electrical element of the work was divided between the louvre supplier and electrical contractor, and materially affected how the BIPV system was integrated into the building.

8.5 Episode 4: detail design

This episode continues from the completion of the pre-contract design order (PCSA) for the micro-inverter BIPV system and the awarding of the BIPV contract to the louvre supplier.

8.5.1 Episode 4: narrative account

The main contractor (BP) recognised that there was an interface between the work packages for the louvre supplier (FD) and electrical contractor (CAT) and met with both contractors before the tenders were let, to agree the electrical demarcations.

> We had to literally follow the cable the whole way from the sun to the panel to the inverter, the whole way down through the system to work out exactly who was doing what. We wrote FD [louvre supplier], we wrote CAT [electrical contractor] on it, and we wrote exactly who was doing each piece along the way until we got to the switchboard.
>
> Electrical contractor (CAT01)

This clarification helped, but there were problems with finalising the location of the combiner boxes and establishing the cabling routes. The louvre supplier (FD) was not prepared to include wiring from the combiner boxes to the distribution room as part of their quotation as the wiring routes between the two were not clear.

> We said our responsibility stops at the end of this box, you can wire across, because at that time, they didn't know how they were going to get the cables from A to B, particularly as you had to go across the atrium from one half.
>
> Louvre supplier (FD03)

The location of the combiner boxes was agreed between the louvre supplier (FD) and the architect (SL), taking into account the structure of the building and also the need to be able to isolate the units easily in case of maintenance.

> Because you want them to be accessible., because within it they're fused, there's obviously a big On-Off switch on the front of it, so if somebody had to go do some maintenance you could just go to that box on the floor, turn it off…because obviously with PVs, if there's sunshine, and this is permanently live…[if] I am now isolated at this point, it makes it completely electrically safe.
>
> Louvre supplier (FD04)

The louvre supplier (FD) worked with the PV electrical supply chain to work out electrical components, wiring and combiner box details. Innovation occurred at several levels:

a) the combiner boxes were purpose-made for the project:

> The combiner boxes are purpose-made for the job, we've designed them ourselves, in conjunction with others. We have our own in house electrical people so we can do a certain amount ourselves, …it's got all the normal connectors inside, all pre-made…as an extra into it, we put a 240 volt socket into it so that if you do need to [is] plug your laptop in to do a test, you can do it there and then.
>
> Louvre supplier (FD04)

b) Junctions, wiring and connectors were designed specifically for the project so that they could be "plug and play", thereby minimising installation time.

> [We] designed those plugs from commercially available plugs…we were speaking to the people who made the cables, and said we'll need a long cable, so they premade us a cable with one end open, because at that point, we didn't know where our combiner box at the bottom was going, so they would make us a cable that was 15 metres long
>
> Louvre supplier (FD04)

Working with the supply chain became an important element to the louvre supplier (FD) and allowed then to innovate. This was summed up in one conversation:

> Making sure that we have a supply chain that can provide us with what we want,…we need to have people who can make that module for us and they're going to make it and it's going to be made as we need it, and it's going to be the right standards, whether it's BS or EN or whatever, and we're only as good as our supply chain
>
> Louvre supplier (FD03)

Using the micro inverters meant that the designated inverter room on the roof of the building became redundant, so the louvre supplier and architect agreed that the distribution boxes from each string of combiner boxes would be sited in the room and the rest of it used for other plant equipment.

> They still used the inverter [room], because you have the two distribution cabinets - these cabinets are about two thirds of the size of that [inverter], and within there you've got, meters, you've got G59, you've got other isolators, you've got surge protection, a whole bunch of other things, so that's it.
>
> Louvre supplier (FD03)

The louvre supplier (FD) worked with the micro inverter company to develop a web-based monitoring system for generation output and inverter performance, The system was initially designed by the micro inverter company to give information on domestic installations, but the two companies worked together to develop it for use in Synergy Court. The two companies also developed the method of labelling and testing the louvres, so that each louvre had a unique identity on the maintenance system and that its state of operation (i.e. "off" or "on") and its output could be monitored. This system was also used to test that each PV panel generated a signal to the system and that the system identified each panel individually.

> So each one of these [louvres] is addressable…we know that "A" louvre is in position "A", so once this louvre is defined to go to this position, it has to be fitted there; you can't fit it elsewhere; and then when the system is switched on, the computer then says yes, I've got all these outputs, I'm receiving data from them all, and if one's not received, we know exactly where it is, straight away.
>
> Louvre supplier (FD03)

The architect (SL) was keen to use a coloured finish on the PV cells to fit with the grey of the aluminium used on the other louvres, but the louvre supplier resisted the change because this would have led to a loss of performance and increased cost. A commercial decision was taken by the main contractor (BP) that blue cells would be used.

> The architect initially wanted grey cells, and they were willing to pay a 20% increase in cost, for 20% loss of performance to have grey, in the end, someone put a commercial head on, and banged their head against a wall and said no, we're not doing it.
>
> Louvre supplier (FD03)

Detailed attention was paid to the design of the aluminium louvres to match the PV panels and the architect (SL) decided to perforate some of the non PV louvres.

> We've got perforated aluminium sheets, and the pattern chosen for the perforation, because the cells are 156 square, like that, the perforated pattern was matched at 156mm pitch, to match this, so it ties in.
>
> Louvre supplier (FD03)

Before the units left the factory they were tested and certified for output with the main contractor. The timing of the testing was in January and low light levels meant that it was difficult to prove the output from the panels against the expected figure.

> We did some factory acceptance testing, we laid them on the ground, we pointed them roughly in the right direction, we connected it all up, and proved to [the architect, design consultant and main contractor] that it works...It was very difficult because we did it in January, when there was hardly enough sunlight to, the worst month to try and do it.
>
> Louvre supplier (FD04)

Part of the detail design work was to develop an innovative way of installing the louvres. Rather than being tied to the main project schedule in terms of hoist availability, the louvre supplier (FD) developed a way of using the building maintenance unit (BMU) hoist to move the louvres. This meant that the main site hoist was only needed periodically to lift batches of louvres to the roof and the louvre supplier was then free to install these at their own pace.

> We've came up with a completely different solution, whereas initially they were saying tower crane, got to lift 2,400 louvres in, we said no we're going to make a platform, put the platform onto your BMU track, and have a crane, on the track, so it would be completely self-sufficient…So instead of having to say, we need 2,400 tower crane lifts of louvres, we went, we need to move the platform 20 times, and we need bulk lifts of 10 louvres, so we need 200 odd lifts, very much reduced, so the tower crane's free for other things and we're independent.
>
> Louvre supplier (FD03)

The louvre supplier (FD) also decided to install the louvres using abseilers so that the electrical cabling could be connected as installation proceeded. This was made easy by the "plug and play" approach taken in designing the wiring systems.

> The only way to install the louvres is to use abseilers, and therefore with a plug and play system, all they've got to do is mount it, plug the two of them together, and run a cable, which is not skilled electrician's work, it's just cable running…and you hadn't got any actual wiring until you can stand on the floor…we didn't want one person to go back and wire them, because that obviously just doubles the amount of time.
>
> Louvre supplier (FD04)

Attention was paid to the need to keep the PV panels clean and the method of doing this. The louvre supplier (FD) had specified that the PV louvres were made from self-cleaning glass laminate and that the louvres could be reached by the cradle of the building maintenance unit (BMU). This was written into the maintenance procedures.

> In calculating your outputs, you have to assume, how often you are going to clean. There are two things actually, yes it'll get dirty, and the output will go down, if you wash them with any sort of detergent it will [also] reduce the output, and so the best way of cleaning them is to have self-cleaning glass, …so that any cleaning they do is from the BMU [building maintenance unit], cradles above and just hosing, that's about all that needs doing.
>
> Louvre supplier (FD04)

This episode ended when the detail design for the BIPV system was complete and installation of the louvres was about to commence.

8.5.2 **Episode 4: technological frames**

As the three parties - the main contractor (BP), electrical contractor (CAT) and louvre supplier (FD) - worked out the boundaries of the work packages, they mobilised the Design Optimiser frame to ensure that no parts of the electrical system were left out. When the issue of cable routing through the atrium to the distribution boxes was discussed, the louvre supplier realised that the route would depend on the as yet undecided internal arrangement of cable runs, and through the Risk Minimiser frame declined to include this portion within the package. When agreeing the location of the combiner boxes, the architect (SL) and louvre supplier (FD) mobilised the User frame to think about how to access and isolate the boxes, rather than adopting either the Design Optimiser frame (thinking about the most efficient way place to locate the boxes) or the most out of sight location to suit the Design Aesthete frame. The User frame was also mobilised by the louvre supplier (FD) and inverter supplier when developing the web-based monitoring system and they considered how the operation and maintenance of the system would work.

When designing the "plug and play" wiring system and combiner box design, the louvre supplier (FD) considered the technology through the Design Optimiser frame and was therefore interested in efficiency of design and installation. Both the Generation Maximiser and Design Optimiser frames were the dominate frames mobilised during this episode. This is reflected in the SCOT diagram (Figure 8-4) which shows that the louvre supplier (FD) and PV laminate supplier (LE) worked closely together to maximise the output from the BIPV system. To counteract the 5% drop in efficiency which resulted from the lamination of the PV cells in the glass, the louvre supplier specified square rather than hexagonal cells to increase the generation area. The louvre supplier (FD) continued to mobilise the Generation Maximiser frame in developing the micro-inverter design and reducing losses by minimising the length of DC wiring runs.

To model the generation output in an efficient way the louvre supplier mobilised the Design Optimiser frame and developed an averaging system based on standard cell numbers and positions of louvres. The architect (SL) had wanted to use grey PV cells to match the surrounding aluminium louvres (Design Aesthete), but gave ground when the louvre supplier (FD) and main contractor (BP) objected in terms of both cost (Cost Watcher) and generation loss (Generation Maximiser). However, the architect (SL) adopted the Design Aesthete frame again when specifying perforations on the surrounding aluminium fins and this time the stronger frame of Generation Maximiser was not used to oppose this. When considering the installation of the louvres, the Time Sentry frame was shared by both the main contractor (BP) and the louvre supplier (FS). Being aware of the impact of the hoist scheduling on the project schedule and the on the available time-frame for lifting the louvres into position, the louvre supplier used an innovative way of adapting the BMU system to reduce this interdependence and thus ease pressure on both themselves and the main contractor.

> So we made a full platform that's steel frame on legs…and we put it onto the BMU track at various locations of the building, put the crane onto it, we had two platforms, one with the crane, one with the materials, so then we could just work independently. It's the whole part of the package for us…going, we're giving you the unique design of the louvres, we're giving you a time saving system to install it
>
> Louvre supplier (FD03)

While considering the cleaning requirements for the BIPV louvres, the louvre supplier (FD) and PV laminate supplier (LE) understood that the dirt on the PV louvres would affect generation of the cells and specified self-cleaning glass as the laminate substrate (Generation Maximiser). The louvre supplier (FD) relied on the PV laminate supplier (LE) to provide recommendations on the appropriate cleaning regime for the louvres (User frame).

This episode demonstrates that although the need to maximise generation (Generation Maximiser frame) continued to dominate problem solving, the Design Optimiser frame allowed the louvre supplier (FD) to consider many facets of the design and accommodate different frames (considering the User frame when siting combiner boxes, and using square rather than hexagonal cells to slightly increase generation (Generation Maximiser)). Being able to understand different technological frames gave the louvre supplier opportunities to develop innovative solutions to tensions between the different frames as illustrated by the development of the BMS hoist system.

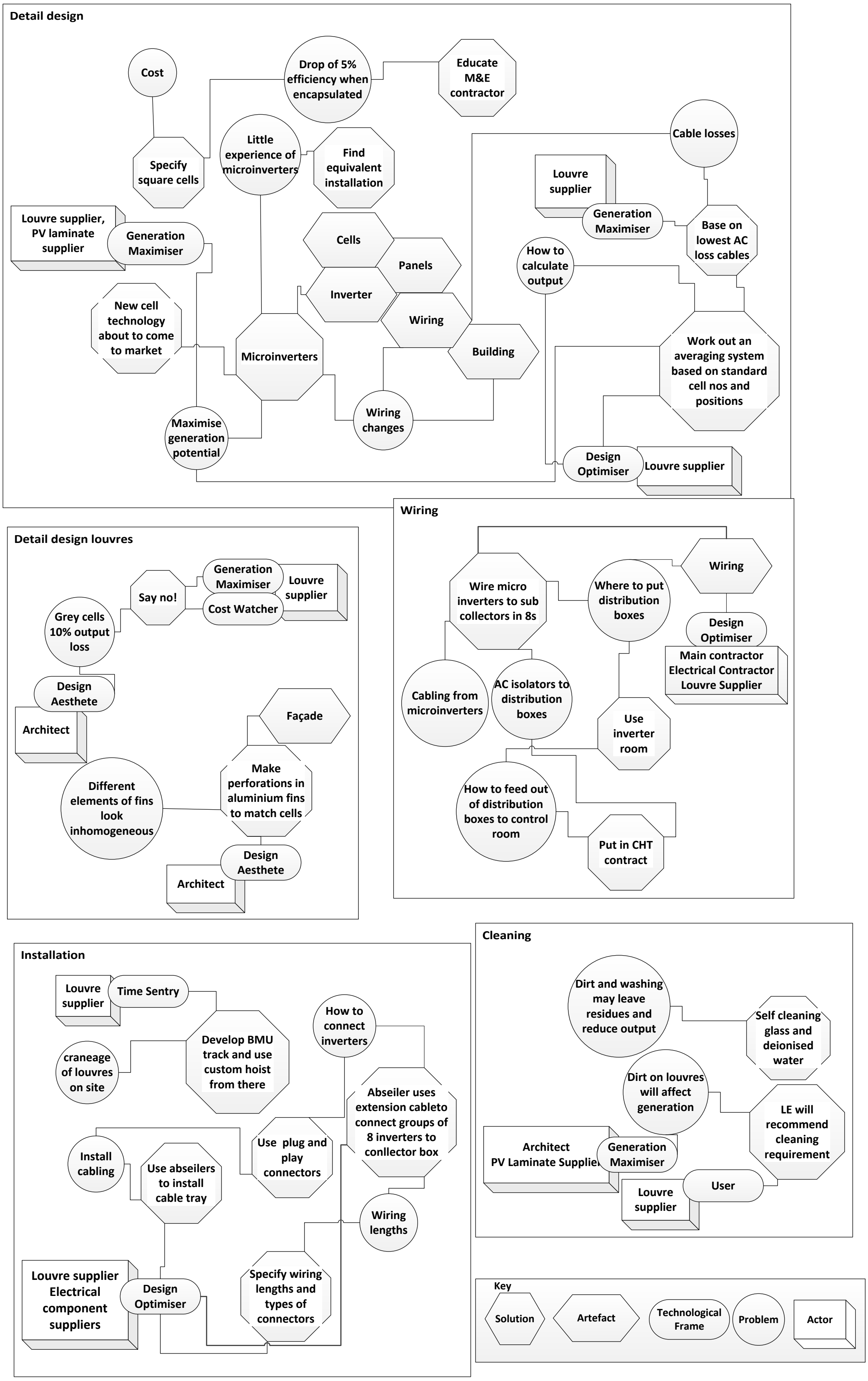


Figure 8-4: Technological frames mobilized in episode 4 (detail design), Synergy Court

8.5.3 Episode 4: co-development

Two clear examples of co-development of the building and the BIPV system occurred during this episode of the project. Both were minor, but the first undoubtedly affected the appearance of the building and also had an impact on the manufacture of some of the non-PV roof louvres.

i. Some of the non-PV louvres were perforated to give the roof an aesthetic look of homogeneity.
ii. The BMU system was adapted to allow for local hoisting of the louvres during construction.

8.6 Episode 5: construction

This episode continues from the detail design of the BIPV system and the start of the installation of louvres.

8.6.1 Episode 5: narrative account

Once installation of the BIPV system began, the electrical work caused particular problems for the installation team. The team consisted of the louvre supplier (FD), the electrical contractor (CAT) and the main contractor (BP). The issue of cable support or containment became pressing as the architect worried that the black cables would show against the grey of the aluminium louvres. Various solutions were suggested: changing the cables from black to grey; painting the cables grey; and finally, using grey containment or cableways to cover over the cables. The louvre supplier (FD) described the situation:

> We had issues convincing the client and the architect about containment, we had issues with the colour of the containment because he didn't like to see cables, he didn't like to see containment, didn't want to see galv he didn't want to see anything apart from the louvre. So they drew the louvre in the building and then they didn't design the M&E around it.
>
> Louvre supplier (FD02)

The eventual solution was developed by the site representatives of the three firms and the process is described below.

> [So who did that design of containment?]…We did it, we developed it and went through the hardship of convincing them [said by Main contractor]…We decided how we were going to do it, how we were going to get the wires, where we were going to put the containment. [said by electrical contractor]….We discuss it and, and we do a sample, and they said, yeah, that's all right. So these boxes here, we ended up putting them on level eight, so we ended up making a system, a structure to fit, put the feed on, so the cable come down the hoop and went into that box and then came back up wherever applicable and back into this space [said by main contractor].

The development of the containment system defined the position of the combiner boxes and their position changed from the original place at the base of the ribs to the position dictated by the containment run.

> That's why the combiner box is there. So we come in, further down, that one wasn't actually fitted at the time, now it is. You can just see the wire.
>
> Louvre supplier (FD02)

The frustration of the decision-making process was described by the main contractor, as the architect insisted on grey cables and containment, and the PV laminate supplier (LE) and main contractor (BP) insisted on black cables and grey sprayed containment.

> [The architect] wanted grey, same colour as the steel. He threw his toys out of the pram and said I don't want any cables, I don't want any containment…we went through a couple of options and said, look, we can't do any better than this, if you want to change anything you need a different system…He wanted sprayed cabling which was colour coded to meet the Rahl number of the steel, which was impossible, because it would degrade over time. Option two was, stick with the black cable and, spray the galvanised trunking, which we ended up doing. So the architect, he had to live with it unfortunately.
>
> Main contractor (PB02]

As the installation work preceded, the gaps between the detail design and the actual build became clear. The difficulty of finding cabling routes from the combiner boxes to the distribution cabinets surfaced, as did the difficulty of satisfying the architect's aesthetic requirements which, when seen from the perspective of the scale of the building, seemed unrealistic.

> There was no design for where that goes; it's quite tricky to put that in the building because it's in mid-air. There was no design to say how we'd get the cable from the inverter down the building, because he goes, I don't care, I don't care how you do it, I just don't want to see it. As if he stands in the street and looks up and sees the cable, and can see the cable there.
>
> Main contractor (PB02)

The discrepancies between the plan and reality were articulated by the installation team:

> There's always gaps [said by electrical contractor]...Yeah, that's right, you get something left out, they never match up, ever [said by main contractor]…The finite detail isn't always there especially to that level…[electrical contractor].
>
> Installation team (BP02, FD02, CAT01)

As a result of not having pre-determined cable runs, and the uncertainty of positions of combiner boxes and containment, wastage occurred in terms of lengths of cables specified by the louvre supplier (FD) who was not in charge of deciding cable and wiring runs.

> We had quite a bit of wastage on it to be honest because they were guestimating where and how it was going to be run.
>
> Louvre supplier (FD02)

As the combiner boxes and distribution cabinets were installed, overlap between the louvre supplier's (FD) work and that of the electrical contractor (CAT) started to emerge. The meter provided by the louvre supplier (FD) was incompatible with the system for the building and needed to be replaced. Other issues of interfacing had to be discussed and refined.

> I looked at the meter and spoke to our EMS [Energy Management System] provider and they [said], well we can't interface with that meter, we won't be able to extract the data from it, we will need third party pieces of kit. So then we got that changed, There's an EPO [Emergency Power Off] system within the switchboard so if there's a problem you could knock off the power within the room, but we then have to interface that with this as well, because this is generating its own electricity. So we've had to interface that with their panel as well, and give them the various details that they need.
>
> Electrical contractor (CAT01)

The installation of the panels did not pose any particular safety issues for the abseilers, but did cause concern when the electrical contractor (CAT) realised that the bare trailing leads from the louvres were live and needed to be made safe.

> As soon as you get that plugged in, it generates straightaway, obviously, as soon as the sun gets on it...And we had them sort of dangling there in the breeze and we put terminal blocks on them to, and taped them, because we were worried about if it got wet and someone's going to zapped as they walked past it.
>
> Electrical contractor (CAT01)

As the installation progressed, the impact of the schedule, and the attention of the Quantity Surveyor (QS) waxed and waned at different stages. This was articulated by the louvre supplier (FD) and amplified by the electrical contractor (CAT).

> At the moment they're not looking at it. They looked at it when we first started putting them in …All lovely, that's exciting, they're going on, and now that's gone off the radar again. It'll only come back on when it starts getting tested.
>
> Louvre supplier (FD02)

> So in terms of overruns both in time and budget, because it's [the PV] not critical nobody really watches it.
>
> Electrical contractor (CAT01)

At the end of this episode most of the PV louvres had been installed and the electrical cabling to the distribution boxes was complete, but the system could not be commissioned until after all the other electrical work for the building had been complete. This was anticipated to be in early 2016.

8.6.2 Episode 5: technological frames

As installation of the electrical part of the system started, two technological frames were mobilised. The architect (SL) (and client) mobilised the Design Aesthete frame, viewing the containment of the BIPV cables as aesthetically undesirable and aiming to minimise the visual impact. The louvre supplier (FD), main contractor (BP) and electrical contractor (CAT) mobilised the Design Optimiser frame, viewing the containment as a non-negotiable necessity to support the wiring and cables. The louvre supplier (FD), electrical contractor (CAT) and main contractor (BP) worked together to develop a solution for containment of the wires which would satisfy the aesthetic demands of the architect (Design Aesthete), whilst making the solution buildable (Design Optimiser). This process of negotiation and the demonstrable understanding by the actors of each other's frames is evident in the interview extracts in 7.6.1 and shows how project actors understood how different members of the team related to the technology differently.

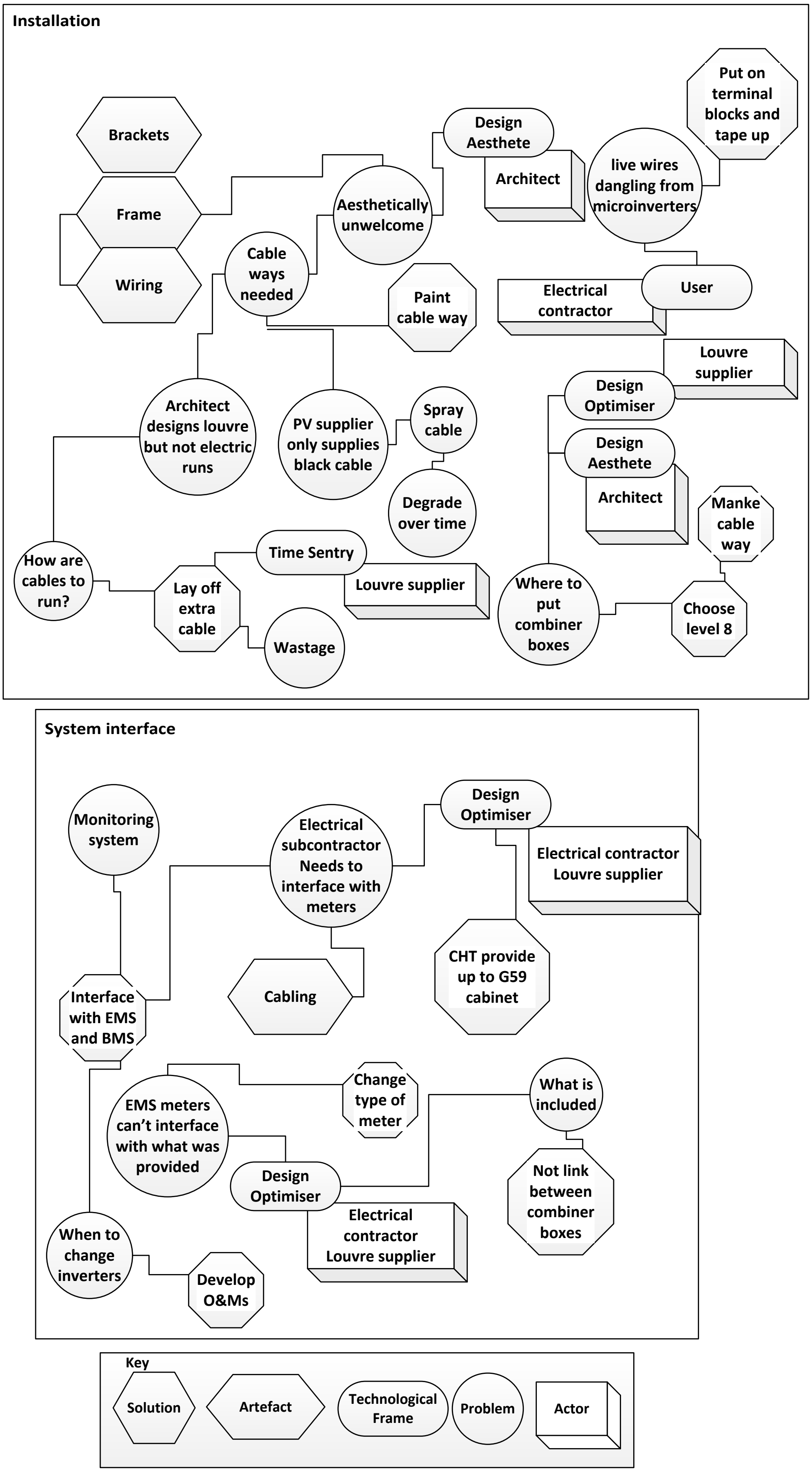


Figure 8-5: Technological frames mobilized in episode 5, Synergy Court

The main contractor (BP) was frustrated by the lack of information available to carry out the design, and the conflicts between aesthetics and design were resolved through a pragmatic suggestion of spraying the containment trunking to match the steel. The installation of the louvres and wiring outstripped the finalisation of the cable and wiring runs, which meant that the length of wiring from each louvre to its combiner box had not been confirmed. The louvre supplier (FD) was keen to progress with the installation (Time Sentry frame) and so “guestimated” the length of wiring needed before laying off each cable. This resulted in wastage when the cables were later run to the combiner boxes, as the length had been over-estimated. The electrical contractor (CAT) mobilised the User frame when he became aware that the laid off cables were live and posed a hazard to the construction personnel working near to the cables. As the louvre supplier (FD) and electrical contractor (CAT) tried to resolve compatibility issues between the G59 meter and cabinet they were both engaged with the project through the frame of Design Optimiser, focussing on getting the system working efficiently and ironing out interface issues.

The analysis above and in Figure 8-5 illustrates how during this episode two technological frames dominated: Design Aesthete and Design Optimiser. The tensions between the goals of the actors mobilising these two frames were heightened by the frame of the Time Sentry which was embodied by the schedule (a social artefact). Whilst negotiations between the Design Optimiser and Design Aesthete frames allowed an acceptable solution to the containment problem to be found, the tension between finding an acceptable route for cabling (Design Optimiser and Design Aesthete) and the need to adhere to the installation schedule (Time Sentry) led to the quick fix solution of laying off longer than necessary lengths of cables, which resulted in unnecessary wastage.

8.6.3 Episode 5: co-development

In this episode there were two examples of co-development between the building and the BIPV system:

i. The main example is the addition of containment and the knock-on effect of its visible aspect. The containment had to be made as small as possible and an additional process of matching the colour to the aluminium and painting was needed.
ii. A secondary occurrence was when the G59 meter in the distribution box had to be replaced in order to be compatible with the EMS system for the building.

8.7 Summary

This final section of the chapter brings together the five episodes to examine the case as a whole - exploring the technological frames and RSG's; the co-development of the BIPV and the building as the project proceeded; and the issues and challenges which were specific to this project.

8.7.1 Technological frames and RSGs

The preceding analysis for each episode illustrated how all the technological frames were mobilised by the actors in the project. It went on to explore how tensions between the actors mobilising different technological frames played out while the actors had to deal with the problems, and the way that they found solutions to these problems. This section summarises the pattern of technological frames used and explores the way that actors mobilise different frames at different times throughout the project.

The Generation Maximiser frame is the most frequently adopted frame in this project, with almost all project personnel being drawn into the frame at some over the course of the project. It is also evident that this frame was the most used when problem solving was needed. There were very few examples of the Risk Minimiser frame being mobilised within the project, a notable difference from the other two case studies. It could be argued that the need to focus on maximising generation potential drove a degree of positive innovation by seeking to minimise the risk of not achieving the generation target. The Cost Watcher frame was not particularly in evidence in this case study - their concerns were mainly overridden by the need to maximise generation and the additional £250,000 needed for the design of micro-inverters was not a factor in decision-making.

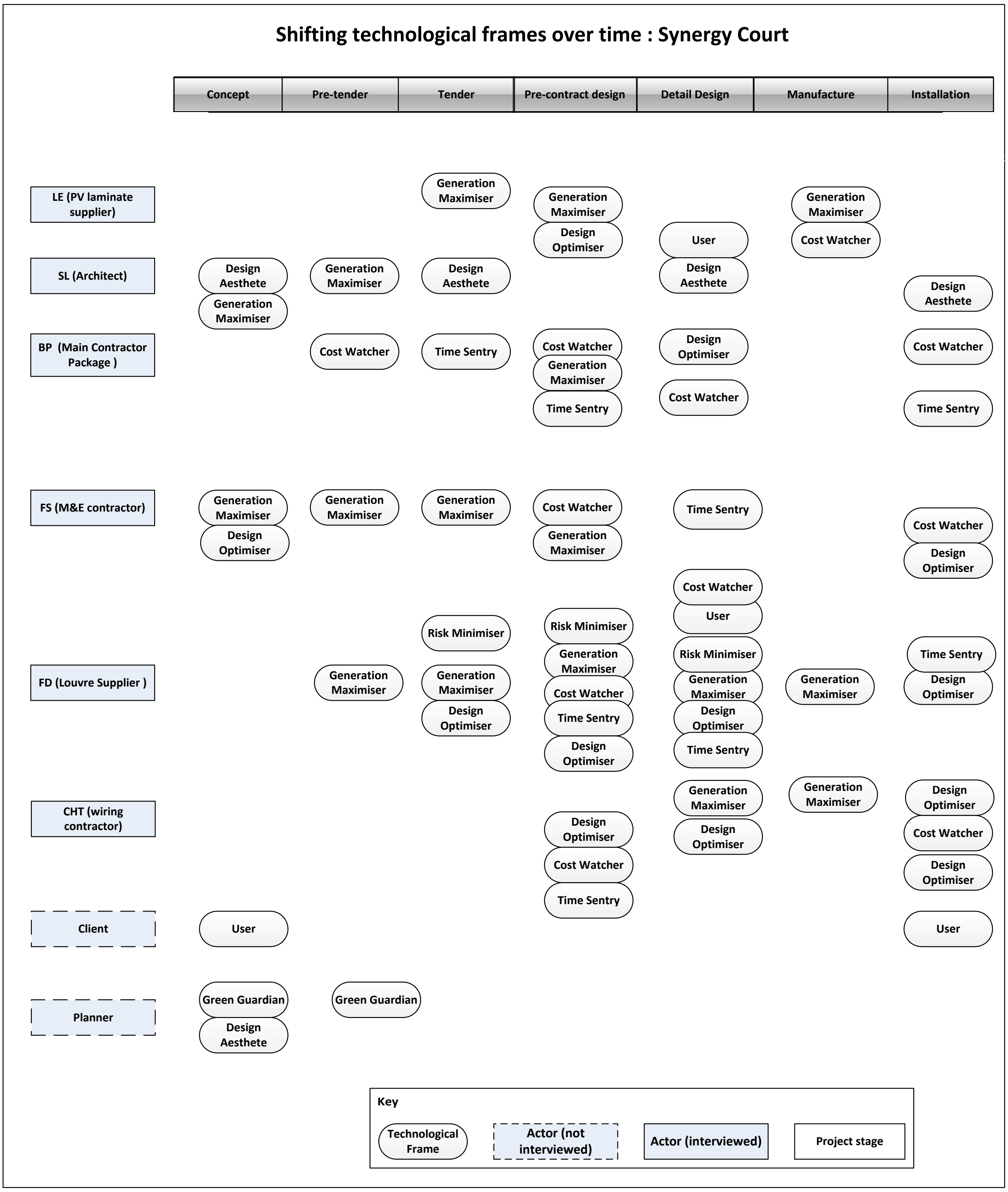
Analysis of all the project episodes shows that many actors changed the technological frame through which they viewed the technology over the course of the project. The most obvious example of this was the architect moving from Design Aesthete to Generation Maximiser at the start of the project. The architect's initial aim of designing a building to fit in with the architecture of the surrounding area was overtaken by concerns with generation potential and meeting the local authority planning requirements for renewables generation. Initially the architect described how the aesthetics of the building drove his design, but subsequently described how the generation potential of the building soon took over as the main driver.

The actors mobilised different frames at different times of the project and pattern of shifting frames for actors is illustrated in Figure 8-6 below. Actors (the right hand column) moved between frames as the project progressed (the time element of the project being represented on the horizontal axis at different project stages). During the concept phase of the project, the planner was the sole member of the Green Guardian frame, whilst the architect, louvre supplier and M&E contractor all shared the concerns of the Generation Maximiser frame.

This was the only time that the architect did relate solely to the Design Aesthete's frame, and this is a distinctive feature of the case study compared to the other two. The louvre supplier largely used the Generation Maximiser frame, but mobilised the Cost Watcher and Design Optimiser frames as well. In the tender design episode, the louvre supplier developed solutions for BMU and for installation hoist mechanisms, while being very aware of cost implications and in getting the correct pricing into the tender. The joint focus of the electrical contractor, main contractor and louvre supplier in maximising generation potential was a unifying force in their problem solving, and drove their solutions towards increasing output and minimising system losses.

Unlike Future Green, at Synergy Court the architect's focus as both Generation Maximiser and Design Aesthete was equally balanced - his concerns were to optimise both the aesthetics of the building and the output from the PV system. The initial rejection by the planners of the building design, and then the lower projected electricity output, made him aware from early on in the concept design that the two were very interdependent. The predominant frame in Synergy Court was that of the Generation Maximiser and this frame united the project team in identifying common areas of concern. The architect understood the relationship between the angle of the louvres and generation potential. The M&E engineers understood the differences between their calculations and those of the louvre supplier. The electrical contractor understood the importance of efficient cable runs and the louvre supplier had to innovate in the quest to achieve the necessary output. The members of Design Optimiser and Time Sentry frames in particular were very fluid, with nearly every actor being part of each of these over the course of the project, but at different times. The dominance of the Generation Maximiser frame was constant throughout the project, but the actors mobilising the Design Optimiser frame followed the stages of the project, as the responsibility for design moved from the mechanical design engineer to the main contractor and then to the louvre supplier as installation started. In this case the Time Sentry frame did not have a major impact on decision-making and the louvre supplier almost de-coupled the PV system from the project schedule by developing his innovative installation solution. The dominance of the Generation Maximiser frame in this case study drove the co-development of the building and PV system, and allowed normal contractual risk aversion to be replaced by innovative design in a variety of areas.

When mapped onto the conventional project stages (Figure 8-6) some shifts in the dominance of a technological frame occurred at transition points; for example, where the project changed from concept to pre-tender design or from design to installation. The architect dropped the Generation Maximiser frame as soon as the PCSA was agreed, whilst the Electrical Engineer moved away from the Design Optimiser frame to adopt the Generation Maximiser frame when a proposal to introduce micro inverters changed the basis for design. These shifts could be accounted for by several factors: the natural change in focus of the project actors as the project moved from concept to installation (the changes could be termed inflection points); the ongoing stabilisation of certain elements of the design (for example the generation potential for the micro inverter system); and the shifts in the nature of the problem (as the roof became an aesthetic design issue and then became a constraint for the PV system). The next chapter will explore these factors further by comparing the different case studies.



Shifting technological frames over time : Synergy Court

	Concept	Pre-tender	Tender	Pre-contract design	Detail Design	Manufacture	Installation
LE (PV laminate supplier)			Generation Maximiser	Generation Maximiser Design Optimiser	User	Generation Maximiser Cost Watcher	
SL (Architect)	Design Aesthete Generation Maximiser	Generation Maximiser	Design Aesthete		Design Aesthete		Design Aesthete
BP (Main Contractor Package)		Cost Watcher	Time Sentry	Cost Watcher Generation Maximiser Time Sentry	Design Optimiser Cost Watcher		Cost Watcher Time Sentry
FS (M&E contractor)	Generation Maximiser Design Optimiser	Generation Maximiser	Generation Maximiser	Cost Watcher Generation Maximiser	Time Sentry		Cost Watcher Design Optimiser
FD (Louvre Supplier)		Generation Maximiser	Risk Minimiser Generation Maximiser Design Optimiser	Risk Minimiser Generation Maximiser Cost Watcher Time Sentry Design Optimiser	Cost Watcher User Risk Minimiser Generation Maximiser Design Optimiser Time Sentry	Generation Maximiser	Time Sentry Design Optimiser
CHT (wiring contractor)				Design Optimiser Cost Watcher Time Sentry	Generation Maximiser Design Optimiser	Generation Maximiser	Design Optimiser Cost Watcher Design Optimiser
Client	User						User
Planner	Green Guardian Design Aesthete	Green Guardian					

Key

Figure 8-6: Movement of actors between technological frames as project proceeds

8.7.2 The co-development of the BIPV and the building

The discussion of the five episodes which marked this case signalled a number of key moments of co-development. The discussion which follows explores the co-development story of the building and the technology in greater detail, and how this mutual articulation occurred. The three types of co-development identified in the previous two case studies (lock-in, homogeneity of appearance, and mutual adjustment and adaptation) also occurred in this case, together with unfolding innovation as the BIPV was integrated within the building. Figure 8-7 illustrates the co-development story by showing the interconnectivity between the elements of the building and BIPV. 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 these. The diagrams which follow were derived from a SCOT framework of analysis, which focussed on the problems experienced by the actors over the project and the range of solutions used to resolve these. Enlarged sections of the diagram figure are used to illustrate specific points in the discussion which follows. Figure 8-7 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.

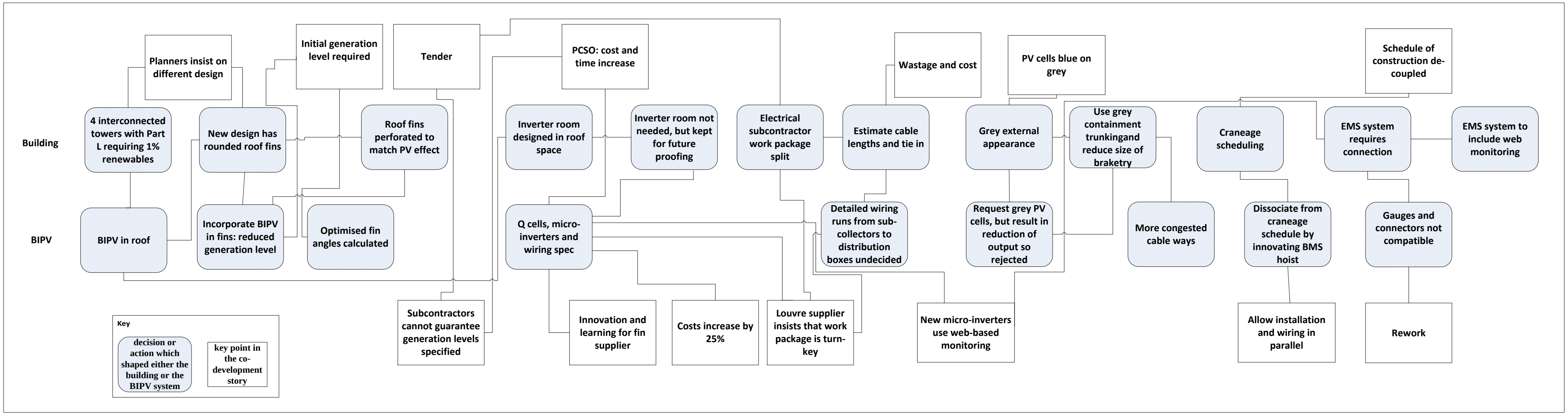


Figure 8-7: Co-development diagram Synergy Court

Lock-in

The lock-in of building shape and BIPV design during the planning and tender stage was the most significant part of the story of co-development.

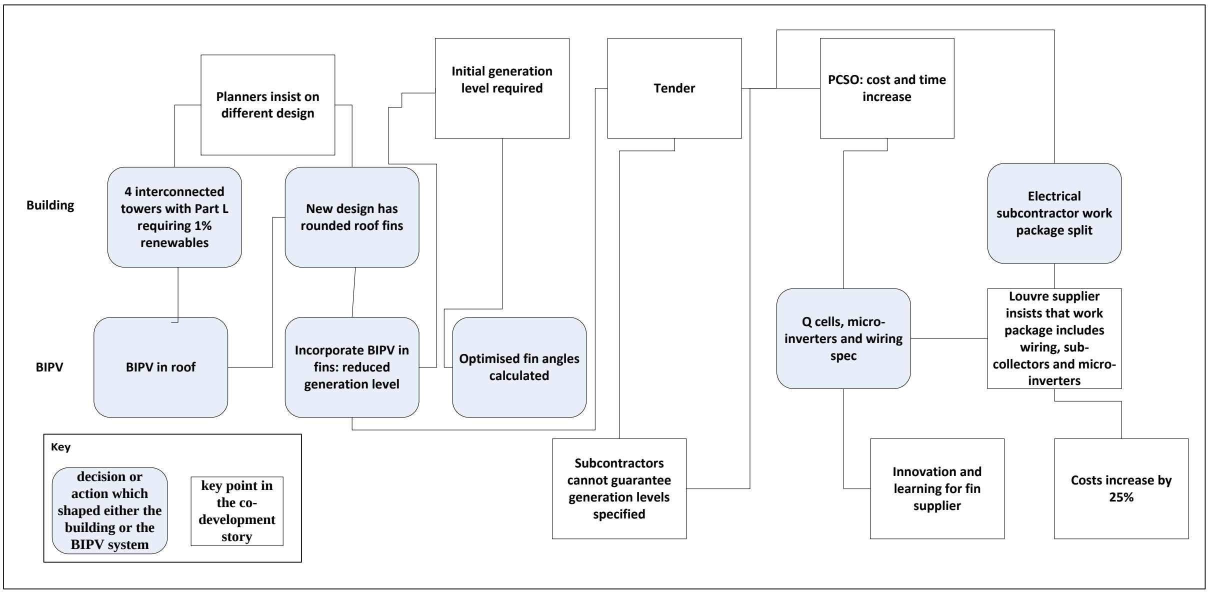


Figure 8-8: Co-development - lock-in

As Figure 8-8 indicates, the client's initial desire to have a research centre with four interconnected towers, and the council's planning policy which required renewable energy generation, locked-in both the inclusion of PV technology and the target figure for electricity generation. The four towers gave a generous roof area to mount PV panels, and the upper south elevation of two towers allowed inclusion of a conventional BIPV system on the façade, which boosted the generation potential. The potential generation figure from this configuration was calculated and submitted as part of the planning proposal. At this point the target generation figure for the building was locked into the project, but no one on the project team realised the significance of this lock in at the time. The louvre supplier project sales manager (FD01) illustrated this point of lock in:

> The planners were sold that output metaphorically…[they say] we'd like some renewable on this building, …[The M&E consultant says] we can achieve this look. Planners say, yeah, we'll have that, and that goes in the plan. Had they said a lower figure that would have been approved, I'm sure, absolutely sure.
>
> Louvre supplier (FD01)

The rejection of the four interconnected tower block design led to the appointment of a new architect and a building with sweeping curved roofs made from louvres, which hid the tower structure and blended the project into its environment. At first glance this was a case of interdependence of appearance, but in fact was lock-in. The new shape defined the available space for the BIPV, but locked-in both the area available for PV generation and the use of BIPV rather than roof-mounted panels. The subsequent decision by the planner to accept the new design, but insist upon the higher generation figure from the old design, heralded a series of mutual adjustments and adaptations. The requirement to generate more electricity and maximise the output from each roof louvre meant that louvre lengths were made as continuous as possible, with each one oriented to an optimal angle in order to avoid shading from the neighbouring louvres and the building. The effect of these adjustments was to give the building roof a distinctive texture and look, and also meant that any louvres which were not PV louvres had to match the overall design. Once the project went for tender, the BIPV louvre suppliers could not guarantee that the required output could be met using conventional configurations, but as the generation figure was locked-in, new ways of meeting the target had to be found. The louvre supplier suggested using Q cells and micro-inverters, which resulted in the main contractor issuing a PCSO which deviated from the normal project procedure and resulted in increased contract costs. The challenge of meeting the generation targets within the constraints of the curved roof shape led to a series of innovative modifications for the BIPV system - from the use of micro-inverters to the design of plug and play cables and the development of a web monitoring system.

> We took on board the architect's intent, and effectively rationalised it to what we thought was a buildable, simple design. A cost effective design as well, both for the PV element, which is only 20% of the louvres, and the rest of the louvres as well, we wanted a simple design that worked for the whole system.
>
> Louvre supplier (FD04)

The final co-development piece of this phase was the insistence of the louvre supplier that the BIPV work package include electrical wiring, supply of micro inverters, combiner boxes and distribution panels. This required change to the projects work package content, and adjustments to the electrical work package in particular.

Homogeneity of appearance

The second series of co-development events relate to interdependence of appearance of the BIPV and the building, and is shown in Figure 8-9. The decision to incorporate BIPV in some of the roof louvres gave the architect concerns about the homogeneity of the roof. To mitigate this he added perforations to the non-PV louvres in order to imitate the pattern of cells on the PV louvres.

The colour of the PV fins was blue, rather than the grey of the aluminium louvres and the architect tried to change these to grey. However, on finding that grey panels were less efficient than the blue ones, he agreed that the blue colour would be specified, which gave the roof a degree of lack in homogeneity externally. Similar concerns to conceal the cables internally meant that the containment channels for the PV wiring were painted grey and that their cross section was minimised to reduce visibility. This resulted in congesting the cables within the containment channels and making installation work more difficult.

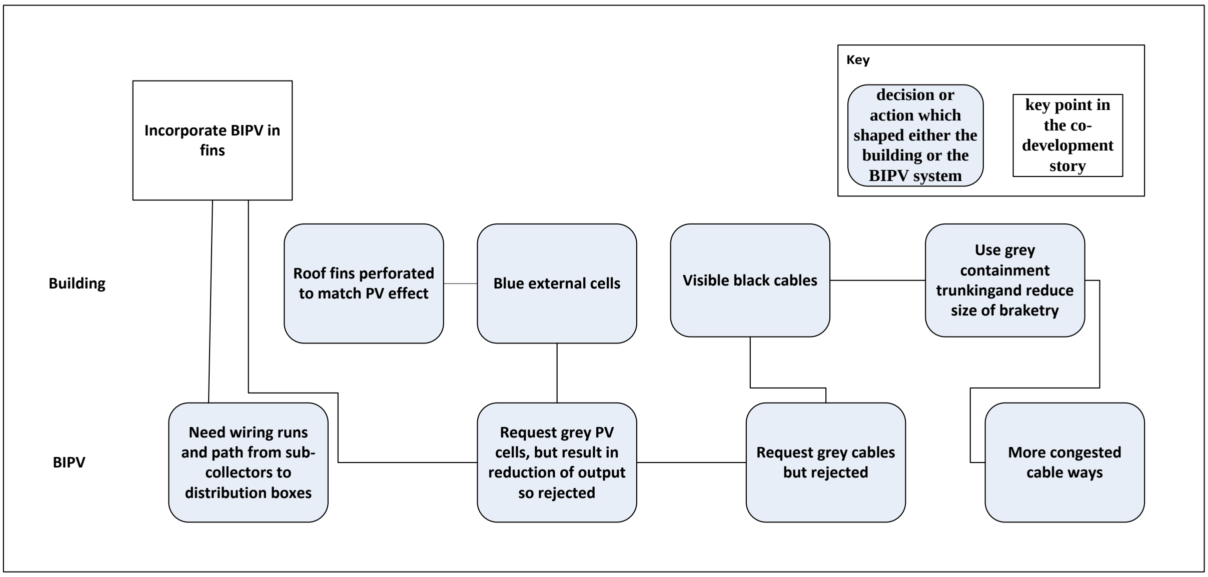


Figure 8-9: Co-development - homogeneity of appearance

Mutual adjustments of the building and BIPV (wiring and cabling systems)

The co-development of the electrical wiring and cabling systems, and the integration of the BIPV into the energy management system is the third example of significant co-development. Figure 8-10 shows the mutual adjustment of the electrical system and energy management system (EMS).

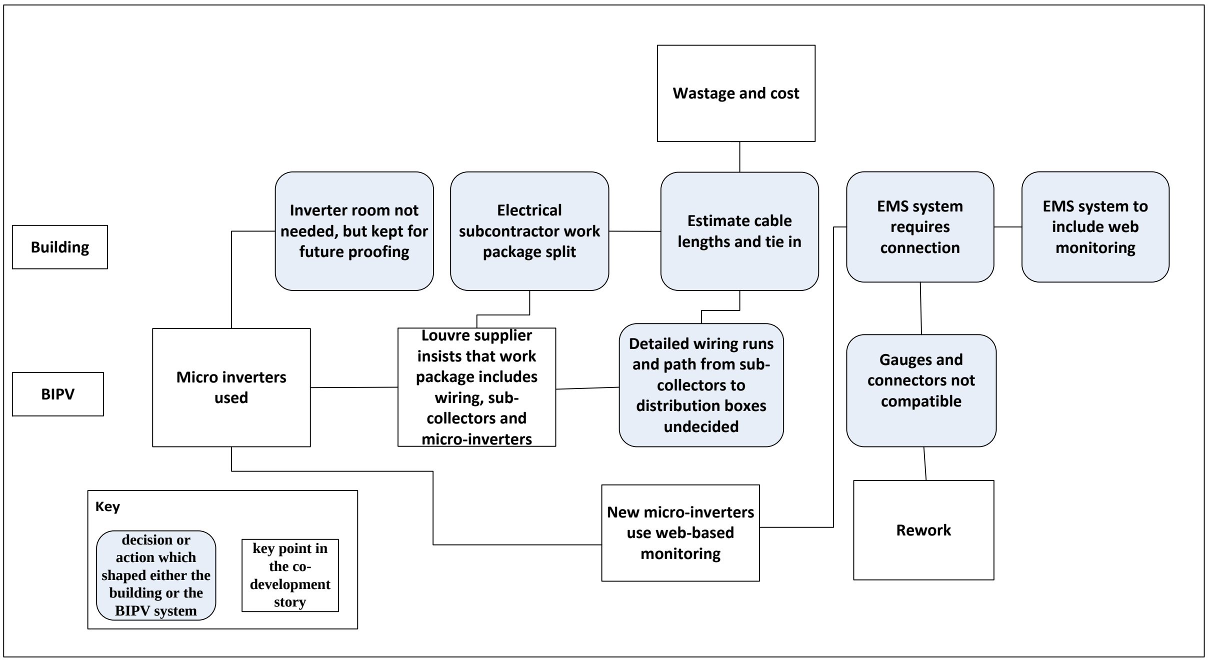


Figure 8-10: Co-development - mutual adjustment 2

The inclusion of micro inverters in the project was identified as the only way to reduce system losses and achieve the target generation potential. The ramifications of this decision were not anticipated and had two major impacts - firstly on complicating the wiring configurations (each inverter now had to be wired to the sub-collectors and so to the distribution panel, rather than being connected in series to the distribution panel) and second, the energy management system would have to incorporate monitoring of all 410 micro inverters. The splitting of the electrical package between the louvres supplier and the electrical contractor meant that the site of the combiner boxes and distribution panels needed to be decided before details of the wiring runs were fixed. The positioning of the combiner boxes was a pragmatic decision which was taken on site just after the louvres were installed. The louvre supplier was ahead of the electrical contractor in terms of installation work and so had to estimate the length of wiring needed from louvre to combiner box, and this led to significant wastage in terms of cabling.

The electrical contractor had no idea how to wire from the sub-collectors (which were on several floors) to the distribution panels (which were in the roof) and so had to develop the scheme. The louvre supplier describes the dilemma of the electrical contractor:

> We knew where the box was here, we knew where the box was there, but we had no idea how to put the cable between the two…Because there's an atrium, and they don't want four cables that are going to be a bundle this size going right through the middle of the atrium. Well each cable here, it was 100 volt cable, so it's only about 30mm diameter, each one, and there will be 10 of them coming from each side, and with cables you have to put them a certain distance apart.
>
> Louvre supplier (FD03)

This series of mutual adjustments and adaptations occurred throughout the installation process as the two sets of work packages came together. The inclusion of the micro inverter monitoring into the energy management system is a further example of mutual adaption and change, as the BIPV system has to be compatible with the building's EMS system, and so a way of identifying each micro inverter was delivered.

The system then had to be re-adjusted when the electrical contractor had to re-specify the type of meter required so that it was compatible with the EMS system and the louvre supplier had to refit the meters.

> Most of the detail comes out once you're here and you've spoken to the relevant people. The panels that these guys were providing didn't necessarily work with the system that we had, so you thrash out the details….they will provide a panel with a meter and we need to interface with that meter, so all the software for the EMS system, needs to be able to read the meter.
>
> Electrical contractor (CAT01)

Procedures of working

The analysis above highlights one other feature of co-development, which involves the way that inclusion of the BIPV impacts and is impacted by the normal procedures of working. Figure 8-11 illustrates this co-development.

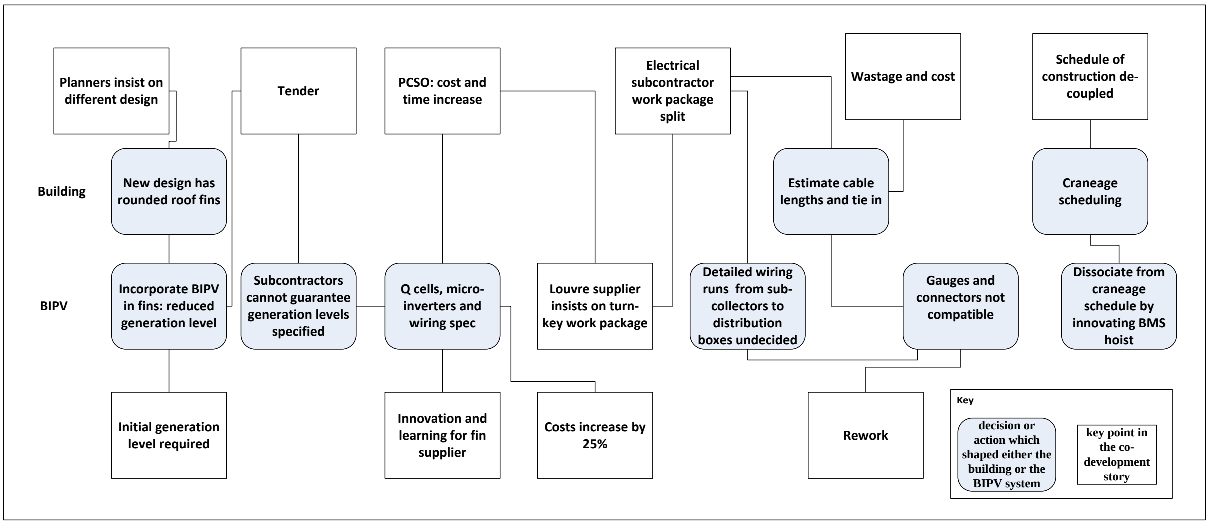


Figure 8-11: Co-development - process

The inclusion of BIPV in the project led to departures from the "normal" project procedures. In keeping with the main contractor's normal procedures, contractors were invited to tender for the various work packages, and there was some negotiation over whether the louvres should be part of the façade contract, or separate to it. The louvre supplier's insistence that the generation targets were impossible to meet effectively stopped "business as usual;" and forced the main contractor to think about a new way to specify and procure the system. A turn-key contract for the louvre supplier to design and install the BIPV system, including the electrical work, meant that changes to the content of other work packages were required. This led to confusion and rework on cable runs and meter fitting, both of which impinged on the electrical contract for the building and meant that the wiring had to fit around the building, and around the atrium in particular. Longer than necessary cable runs in general cause system inefficiencies, but these were reduced by virtue of the micro inverter system because AC systems in general lose less per meter of cable than DC systems.

This series of mutual adjustments and changes to the project procedures and processes led to two outcomes. First it allowed a space within the mechanism of the PCSA to develop an innovative solution that could be packaged together. This included a novel plug-and-play system of cabling and the web monitoring system. It also led to the development of the BMU cradle system to de-couple the installation of the louvres from the general hoist schedule of the project. Secondly it gave rise to an innovative and time saving installation procedure using the BMU hoist to reduce reliance on the site crane. This development only came about because the louvre supplier had to consider installation of both louvres and the electrical work, and wanted to come up with a way to improve the efficiency of the installation of both of these elements.

In summary, each of the four examples of co-development in Synergy Court illustrate the three types of co-development identified in the previous case studies (lock-in, interdependence of appearance and mutual adjustment and adaptation), together with examples of unfolding innovation as the BIPV was integrated within the building. These mechanisms, and reflections of their importance on innovation, are discussed in the next chapter.

8.8 Issues about BIPV and the challenges which it poses for project teams

In line with the other two case studies, there were several issues which have particular relevance for construction projects. This analysis shows five main issues surrounding the adoption of BIPV in the building which were present throughout the project: unfamiliarity with the technology, the presence of a PV expert; the motive for the inclusion of BIPV; the effect of social artefacts; and construction project practices.

The architect and M&E designer were relatively unfamiliar with BIPV, but because of planning requirements were forced to think about generation potential at a very early stage of the project. Unfamiliarity with modelling packages and standards for BIPV created an over reliance by the architect and M&E consultant on new software, which led to several unanticipated consequences with profound implications on the subsequent direction of the project. The louvre supplier explained how errors in calculating generation potential came from a lack of understanding of PV technology.

> Mainly the biggest mistake that they made was [they] used their own programme for calculating output, and no-one could understand why…and their system took weather data that's used for air conditioning, and therefore it was giving much higher outputs , and it didn't take into account the project's in London. It assumes the project's in a place like Cornwall where you would get better yields. It was crazy."
>
> Louvre supplier (FD04)

This was compounded by a lack of understanding of how to apply efficiency calculations which meant that the M&E consultant overestimated the efficiency of the system by between three and five percent. The louvre supplier described how this discrepancy occurred.

> Yes the cell has got a 17% efficiency, but once you encapsulate it in glass, it will [drop to 12%] once you measure it on the output side.
>
> Louvre supplier (FD04)

These inaccuracies at the concept stage of the design meant that the louvre supplier refused to guarantee the output required in the specification and proposed a different system using micro-inverters and "Q" cells, which in turn led to the placing of a PCSA and in the end resulted in a twenty-five percent increase in the package price.

Unlike the other case studies, in Synergy Court there was a perceived PV expert on the project - the louvre supplier. In reality, the louvre supplier was gaining expert advice and support from several sources (the PV laminate supplier, the micro inverter supplier and the cable supplier). This was a clear strategy adopted by the louvre supplier and used as a point of difference in winning the bid. In articulating the reasons for adopting this approach, the louvre supplier mentioned in particular the way that this approach gives the client one clear point of contact.

In this case the two factors which drove the design of the building and BIPV system were: i) gaining planning consent in an area of sensitive architectural considerations and ii) achieving the planning authority required generation output from the BIPV system. The motive for achieving the generation target kept the project team focussed on achieving that goal and this made it possible for novel, more expensive solutions to be introduced and for the BIPV to be integrated fundamentally into the building. This focus on generation and output could be said to have put the louvre supplier and electrical contractor in the driving seat in terms of adaptive innovation - for example, about whether blue or grey cells could be used, or that containment would be used to support cables.

In this case study, unlike the others, considerable attention was paid to the technological assemblage of the BIPV system, under the umbrella of maximising generation potential. The louvres were considered in terms of their generation capacity. Maximising cell placement, specifying new “Q” technology, and specifying square rather than hexagonal cells were all part of the consideration for the system. As part of the focus on generation potential, the electrical part of the system was developed to maximise conversion efficiency, minimise system losses and monitor output. This commitment to install a system that delivered the required electricity was demonstrated not only by the louvre supplier, but by other members of the project team.

> No, there was an output defined, and this is going way back.
>
> Main contractor (PB02)

> They set four louvres up, and we put a flash on and see what the output was. It was a case of, does it meet, tick, yes, if it failed it'd have been a big problem.
>
> Main contractor (PB02)

> That's it, it's all about the output at the end of the day.
>
> Louvre supplier (FD02)

> So when we came onboard we knew we had to hit a certain output and to get to that output we had to prove that we could incorporate that many PVs.
>
> Architect (SL01)

> So, we've tested the system, well a mock-up part of the system, and I think everyone was fairly confident that, once it's on site it should deliver what everyone wants it to.
>
> M&E consultant (FS02)

The most evident social artefact throughout the project was the part L planning requirement for 1% renewable energy generation. It played a huge role in shaping the co-development of the building and the BIPV, and remained in everyone's mind throughout the project. The project schedule absorbed the PCSA and the rework associated with cable runs and compatibility of meters, and the innovative use of the BMS hoist to reduce call on the site crane-age meant that installation was effectively de-coupled from the schedule and could carry on at the pace dictated by the abseilers.

These four issues were present in the other case studies and will be discussed in greater depth in the following chapter.

Construction Practices

The three themes of contracts, continuity and collaboration; and changes to specification which were apparent in the first two case studies were also present in this case study, but in a slightly different way.

The louvre supplier was invited by the main contractor to tender for either the whole façade package or for the roof louvre package, and the other contractors were offered a similar choice. This demonstrates an initial willingness by the main contractor to take a flexible approach to defining work packages and allowing firms to decide on their areas of expertise, and then working out how to knit this patchwork together. Similar flexibility was demonstrated by the willingness to consider changing the specification and introducing micro inverters - arguably the imperative to achieve particular generation figures helped to establish this flexibility. Once again the main contractor demonstrated flexibility in the approach to work package allocation, by allowing the louvre supplier to supply a turn-key contract on the BIPV system, even though this impacted on the electrical work package.

The louvre supplier used a long-standing collaborative relationship with the PV laminate supplier to discuss possibilities for achieving the required generation, but was very happy to establish new relationships with the micro inverter supplier and the wiring supplier.

> But that sort of information is where [the PV laminate supplier] are a huge help to someone like us. It’s not our forte to be honest…we see them as someone who has huge knowledge of PVs and PV systems, and we use that expertise.
>
> Louvre supplier (FD02)

> The person who was their senior technical person ..was literally sat in with us and then we had half a dozen of their engineers sitting in…And we worked with them, to come up with a solution using micro-inverters, so we're changing, we're inverting it to AC at the point of generation, so that was then being linked down to AC.
>
> Louvre supplier (FD03)

Change orders in this case study were discussed in a positive light, parties recognising that what was specified at the start of a project was often changed when the project was built, and a more collaborative approach was taken in working out the next best way forward.

> Because FS wrote the spec [about two years ago] and it's extremely vague…it developed itself over four years and by the time they actually come to install it the spec is chalk and cheese. So once we literally got the schematic, went through it… and wrote the responsibilities."
>
> Main contractor(PB02)

In a similar way to previous case studies, where wiring improvements and inverter developments improved generation potential, the new "Q" cells in this case study allowed the supplier to meet the target generation and were factored into the bid before they were on the market.

> Now we had, we were given some confidence because I think the output on cells at that point was less than what was about to come on to the market. The efficiency of the cells, I think, they keep going on up all the time…But certainly things were happening which would help us.
>
> Louvre supplier (FD01)

These challenges for construction practices when new technology is introduced are common to all three case studies and are discussed in the following chapter.

Chapter 9: Cross Case Analysis and Discussion

The literature review (Chapter 3) established the need to understand more about integration and the dynamics of adoption. The analysis of the three case studies (chapters 6, 7 and 8) indicated that these two themes were important in accounting for differences in outcome between the three projects. This chapter's further exploration of these themes across the three projects will be used to inform the next chapter's re-engagement with literature on innovation adoption. In this discussion the dynamics involved in the mutual articulation of the technology and buildings highlight particular challenges for construction projects and renewable technologies, as increasingly complex, innovative technologies are integrated into buildings.

9.1 Case study comparison

Although the three case study projects were all procured using Design and Build contracts and were constructed over the period 2012 - 2015, the outcomes of all three were very different. The following section discusses the different motives for the specification of BIPV and the different procurement decisions taken for each case study, and summarises the consequences of these. Table 9-1 summarises the motives, procurement strategy and outcome for each of the case studies.

Vogue Terrace

Local planning requirements in 2010 did not establish particular generation targets for renewable energy; instead they called for a sustainability review which included consideration of renewable technologies. BIPV was specified on Vogue Terrace both to satisfy these planning requirements and to provide an up-to-date appearance of the building. In terms of procurement decisions, the client specified that the same contractors be used as on previous phases of the project (which had not incorporated BIPV into the building). This decision locked-in the fact that the façade contractor had no previous experience of using BIPV. This lack of experience of BIPV led the façade supplier to refuse to include BIPV in their work package; which forced the main contractor to re-distribute the BIPV portion of the work package across other work packages. The resulting decoupling of the BIPV and façade led to the further division of the BIPV contract into visible (the panels and bracketry) and the invisible (the wiring, inverters and cabling) sections.

As part of this de-coupling of the BIPV system, the PV panels were free issued to the façade supplier and the electrical portion of the system was put together as a separate wiring package. Unfamiliarity led the main contractor to delay issuing the wiring tender, which led to unanticipated knock-on problems for the integrated design of frames, bracketry, and wiring. The result was that the BIPV was treated as a bolt-on installation, with the BIPV louvres being bolted to the glazing units and the wiring running vertically and externally up the building to the roof mounted inverters. The electricity generated by the BIPV system was not part of the planning requirements, only roughly estimated and was never measured.

Future Green

Future Green used BIPV to win funding from the European Regional Development Fund (ERDF), to make a sustainability statement, and to attract tenants to the building. The requirement for funding was that the building achieved at least BREEAM Excellent and an EPC rating of at least “B”. These certification schemes set the minimum PV generation target as a square meterage requirement, rather than as an output of kilowatt-hours (kWh). The unit of measurement (square metres) reinforced the function of the BIPV as being a green statement rather than to generate electricity. In terms of procurement decision, the main contractor apportioned work packages as though the BIPV system was “just a set of windows”. Accordingly, the BIPV system was divided into two parts - the panels being part of the façade contract, whilst the electrical part was included in the M&E contract for internal work. The content of these work packages was developed by an M&E consultant who included a considerable design portion of work in the work packages. The main contractor was not aware of the requirement for design portions in either of the contracts and so did not check that these designs were developed.

The façade contractor subcontracted worked with the glazing supplier to develop the frames for the façade (including the BIPV panels) and the BIPV panels were assembled into the frames on site. Delays occurred on-site as the site project team (main contractor, façade contractor and glazing supplier) worked out how to get the PV glazing panels into the façade frames and how to get the PV wires inside the building. The M&E contractors had not read the design portion and consequently had not considered how to configure wiring the strings of PV panels and had not sized or purchased the inverter. The overall result was that the BIPV windows made a strong, visible “green” statement but that their functionality was severely compromised - they were essentially opaque, generated very little electricity, and the letting manager found them to be a barrier to attracting tenants.

Synergy Court

Synergy Court was planned as a flagship research centre. Local, negotiated planning requirements demanded that 1% of the electricity requirements of the building be generated from renewable technology on-site. BIPV was included on the building to meet these conditions and as part of the client's sustainability strategy. The external shape of the building, and therefore the area which could be used for PV generation, was fixed in the initial discussions with the Council's planning office. This external shape made meeting the target generation figures very difficult and required detail design of the BIPV system before the work package contracts could be let. The work packages initially had the BIPV louvres included within the roof louvre contract and the electrical work within the general electrical contract. Because of the particularly stringent generation target, the façade contractor suggested an innovative design using micro inverters and sub collectors, and insisted that the electrical work was included within the louvre work package as a turn-key contract. The result of this procurement decision was that the BIPV system became an integral part of the building and was a flagship technology within the flagship building. The generation potential of the BIPV system was designed to meet 1% of the building's energy needs and was connected to the building's energy management system, allowing web monitoring of the electricity generated.

	Vogue Terrace	**Future Green**	**Synergy Court**
Motive For BIPV	- Modern aesthetics - Sustainable strategy	- Funding requirement - Sustainability statement	- Planning requirement (1% of building energy use to be generated by renewables)
Generation Target	- None	- 50 m^2 PV	- 221 MWh
Procurement Strategy	- Previous supply chain - Decoupled work packages - Free issue PV panels - PV wiring	- De-coupled work packages - Visible (PV windows) - Invisible (electrical)	- Changed from de-coupled work packages to turn-key BIPV design
Outcome	- Bolt-on BIPV - Reduced generation	- Sustainable statement - Semi-opaque windows - Minimal generation	- Innovative and integrated BIPV - On-target generation potential

Table 9-1: Summary of motive, procurement strategy and outcome for each case study

The following analysis will explore the types of integration which occurred and the dynamics of co-development in more detail.

9.2 Types of integration of the technology and the building

The literature review established the need for integrated technologies to be integrated within the local context and suggested that challenges of integration could be considered in several different ways: supply chain integration (Wolstenholme, 2009); project team integration (Briscoe & Dainty, 2005); and information and process integration (Rothwell, 1994). Analysis of the case studies gave empirical, micro-level data which allowed a better understanding of three of these types of integration during the adoption process.

i. Integration of technology; how the parts of the BIPV system were considered as a whole rather than as individual components and how the BIPV system was integrated within the fabric of the building.
ii. Integration of the project team; how the relationships between actors, the role of the systems integrator and the presence and locus of BIPV expertise affected the adoption of BIPV.
iii. Integration of project processes; how the relationship between key project tasks influenced the adoption of BIPV. These tasks included: tendering; specification and design; procurement; installation; and commissioning.

9.2.1 **Integration of technology**

With BIPV there are two systems of technological artefacts to consider: the interaction of the elements of BIPV technology (the panels, inverters, wiring and metering systems); and the interaction between the BIPV technology and the building components within which it fits.

The integration of the BIPV technology as a system occurred in only one of the case studies. In Vogue Terrace the electrical and mechanical components of the BIPV system were developed separately. Both were loosely specified at the tender stage of the project by the main contractor’s M&E designer, but the detail design never considered them as a matched system. In addition, at installation the components differed significantly from the original design, and this reduced the generation potential of the system. In Future Green, the design team focused on the BIPV glazing panels at the expense of the electrical system. The result was that no-one considered the system as an integrated whole. The BIPV glazing panels were the focus of attention and although the electrical component of the system was included within the electrical design specification at tender, this design work was never completed and the inverter design and wiring routes were only developed at installation. Synergy Court began as a project where mechanical and electrical components were specified within separate packages, but the technical difficulties in achieving the required generation from the louvres brought the whole BIPV system under review. This review led to the specification and development of micro-inverters and the detail design of all wiring and control components within a central BIPV package. This project was the only example of an integrated approach to installation of BIPV. The difference between these case studies draws attention to the difficulty of reappraising the whole BIPV system performance once project work packages have been set.

Two common ways of dividing project work between the project team had major effects on the integration and performance of the BIPV system. Dividing the BIPV system between mechanical and electrical disciplines had the effect of distributing responsibility for different parts of the BIPV system across multiple work packages and complicated both design and installation. Also, work packages were often defined and tendered for before detail BIPV system design took place. This locked-in the component technology and its configuration before other available integrated options could be considered.

The second area of technological integration to consider is that of the BIPV system and the building. Although it might be intuitive to assume that the specification of an integrated renewable technology would automatically lead to the co-design of the BIPV system and the building, the data does not support this. Instead the case studies showed that the BIPV and building were designed independently, only coming together at the points at which parts of the BIPV system physically joined the building - referred to here as “integrating interfaces”. An example of this was on Future Green, where one integrating interface was the point where the BIPV wires meet the glazing frames. Another example was in Synergy Court, where an integrating interface occurred where the wiring from the collector boxes joined the distribution panels for the building.

Vogue Terrace used BIPV as brise-soleil, which was specifically designed to be bolted on to the windows using brackets. The main contractor and façade supplier purposely separated the design of the BIPV brise-soleil from the design of the façade work package and viewed the two as a bolt-together assembly. The only artefacts that shared design input from both the electrical and façade designers were the glazing bracket and frame. Neither of these two artefacts had been considered to be part of the BIPV system, but because the wiring had to be hidden, they became an unexpected integrating interface. A similar conjunction of frame and wiring occurred in Future Green, but this occurred so late in the project (at installation) that the frames were seen as a barrier to getting the wires into the building, and were drilled through to facilitate the process.

The level of integration of the technology and the building in Synergy Court at first glance appears to be an exemplary counterpoint to the other two case studies. The BIPV technology was procured through one supplier who designed the louvres, wiring, inverters and metering as one integrated system to deliver a particular amount of electricity. On closer inspection this apparent integration masks the early divergence of building and BIPV design which occurred when the architect introduced the new curved roof onto the building. This change prompted the dramatic change in technology and procurement decision, as the main contractor and louvre supplier realised that the new roof design meant that the target generation figures would be difficult to achieve. In this case the façade supplier took the integrating interfaces (for example louvres and brackets, or inverters and wiring) into account at the time of design. This meant that the co-development of the BIPV system and the building took place in an incremental and non-disruptive way.

This discussion of integration of technological highlights two main points. First, the technological integration of the BIPV system, both with itself, and within the building, was heavily affected by the timing of work package definition and the division of work within the packages. Secondly, timely consideration of the integrating interfaces between the building and the BIPV improved technological integration.

9.2.2 **Integration of teams**

A comparison of the three cases highlights five aspects of project team integration which impacted on the adoption of BIPV. These were: previous relationships between contractors; mechanisms used in the project to drive integration; decision-making by contractors; attitude towards the technology; and the perceived location of expertise. Whilst these aspects of project team integration are mentioned in broader literature concerned with project team dynamics (discussed in Chapter 3), this discussion focuses specifically on their impact on differences in the incorporation of BIPV across the projects.

Previous relationships

In each of the case studies, previous relationships between suppliers and project team members affected the integration of BIPV. The client for Vogue Terrace had specified that the same contractors be used on the final phase as had been used in the preceding two. This meant that the project supply chain was fixed in advance and also locked-in the lack of experience with BIPV. The existing relationship between the façade supplier and the main contractor led the main contractor to accept the façade supplier’s refusal to supply the BIPV system without critical appraisal. The acceptance by the main contractor that the BIPV system should be de-coupled from the façade contract had major effects on the project later on. In Future Green, the architect and glazing supplier had worked together before. This was a factor in the architect’s decision to accept a substitute technology from the glazing supplier without exploring the technical implications. It was only later that the architect realized that the change in technology would impact both the appearance of the building and the functionality to the BIPV system. In addition, the previous relationship between the façade supplier and the glazing supplier appeared to lull both parties into a false sense of security that each was designing the BIPV system, when in fact neither was doing so. A parallel dynamic can be found in Synergy Court where the architect and design engineers worked so closely to develop a programme to calculate the potential output of the PV louvre panels that they both failed to check that the standard parameters used in the programme were in line with those used elsewhere. What seems to be true in all of these cases is that previous good working relationships between contractors masked the early identification of problems and resulted in the adoption of short-term, apparently easy fixes rather than an appreciation of the overall impact of decisions.

Mechanisms to drive integration

A common theme in the three cases studies is the occupational position of the BIPV systems integrator. The term “BIPV systems integrator” refers to the actor who finally came to terms with the integrated nature of the BIPV technology and who then drove its integration in the project. Each project had an actor who fulfilled this function, but their occupational position varied, as did the stage within the project at which they engaged with this role.

In Vogue Terrace, the separation between the building and the BIPV system largely stemmed from the façade supplier’s desire to avoid the risk of supplying a novel technology, and the main contractor’s willingness to free issue BIPV panels to the façade supplier for cost and time reasons. The architect adopted the role of systems integrator, by liaising with the PV laminate supplier to develop the brise-soleil panel and with the façade consultant to explore ways to bring the wires inside the building. Subsequently the electrical contractor (who was brought in late in the process) also filled this function; it was his understanding of the total BIPV system that brought the team together to develop a solution to this issue. The systems integrator function in Future Green was largely absent, until taken on de-facto by the main contractor when problems began to appear as installation started. In Synergy Court the louvre supplier insisted on taking on the function of systems integrator, believing that this was a way to guarantee meeting the generation target and of ensuring that the BIPV system and building formed a cohesive whole.

There is a growing literature on the need for an integrator role to deliver sustainability (Rebelo et al., 2013). Often this role is ascribed to the project manager, but this discussion shows that the function shifted through the project span, residing in different actors at different times and for different reasons. This discussion also suggests that the function of the systems integrator is an informal role within the project and that it is one which moves between actors within a project. The way that the integrator role played out across the project was different for each case study and this may account for many of the differences in project execution. The case studies showed the importance of the systems integrator and revealed some of the dynamics involved in how the role developed in the projects. However this was not the thrust of the research and further analysis and research would be needed to explore this area further.

Decision-making and problem solving

Following from the observation that the systems integrator is a shifting function within a project team, it follows that the alliances of contractors involved in decision-making around the integration of the BIPV system and the building also change. What is interesting is that this pattern was different in each case study and did not necessarily follow the systems integrator function. Although each case study used a Design and Build contract, each one operationalised the contract differently by dividing risk and responsibility in different ways. After tender Vogue Terrace was run by the main contractor and the architect was novated across to work for the main contractor. This made the main contractor the formal point of all decision-making, but gave rise to fragmented communication and decision-making. The architect could only communicate with the BIPV laminate supplier though the main contractor, and the façade supplier had to raise issues with the main contractor, rather than have direct discussions with other contractors (for example, with the BIPV louvre supplier when establishing the positions of fixings and connectors, or with the electrical supplier when discussing the cable and connector sizes and configurations). This indirect approach to problem solving gave the main contractor absolute control, but resulted in delayed decision-making and a desire to “fence off” parts of the design to mark limits of responsibility.

Future Green had no procedure of novation and the architect and M&E design contractor remained outside the main contractor’s organisation. Decision-making was fragmented: the architect and the glazing supplier made decisions regarding technology and layout; glazing supplier and façade supplier made decisions about location of wires and connectors; and the main contractor and M&E contractor agreed location of wiring runs and inverter. This resulted in many independent decisions being taken without regard to the wider issue of integrating the BIPV system and the building. The responsibility for the integration of the systems contractually rested with the main contractor, but a lack of an understanding of the BIPV system meant the impact of each seemingly small decision was not recognised.

Vogue Terrace and Future Green both had a fragmented problem solving approach, which revolved around risk minimisation for each contractor. In the case of Vogue Terrace, this changed when the electrical contractor came on board the project and acted as the systems integrator, and facilitated integrated problem solving between the contractors. Future Green did not have a systems integrator until late on in the project and this meant that problem solving occurred on site, at the point of installation.

Synergy Court had a clear and consistent system integrator in the form of the louvre supplier and this gave shape and consistency to decision-making. The louvre supplier, laminate supplier, inverter supplier and wiring suppliers formed one loop to develop integrated specifications for each component of the BIPV system. The main contractor, louvre supplier and main electrical contractor formed another loop which took decisions about the mechanics of how to integrate the BIPV system within the building. It would appear that Synergy Court, uniquely amongst the case studies, used an integrated approach to solve problems before they became issues, but this degree of integration was only achieved after a PCSO had been issued to correct the mis-specification of the BIPV system at the tender stage. In construction projects PCSOs are usually avoided by the main contractor as they are considered to add cost to projects. It could be argued that in Synergy Court the PCSO enabled system integration and was of benefit to the project, allowing generation targets to be met.

This discussion suggests that the function of the systems integrator not only gave energy and direction to the integration of the technology within the building, but was also central to decision-making which considers the building and BIPV system as a whole. It is this integrated decision-making which marks the differences in outcomes of the three projects.

Attitudes to technology

When considering the team's relationship to the technology and the effect that this might have on the integration of the technology, it can be seen that the project teams in each of the three cases had very different attitudes to BIPV and that these permeated all levels of the project. The Vogue Terrace team viewed the technology as "nothing special" - a technology that had been used before and posed no significant challenges to the standard ways of working. BIPV was seen by the Future Green team as a token technology with a negligible contribution to energy generation, and as such the challenges of integrating the technology and the building were dismissed as trivial. The focus of generation targets for the Synergy Court team meant that the technology took on a "must have, must perform" meaning. This focussed the team view of the technology as a challenge which needed to be understood and which required careful integration within the building. These differing views towards the technology reflect the motive of the actors and the degree of integration of the technology and building.

Location of expertise

Finally, when considering the integration of the team, the case studies differed in the locus of perceived expertise. The Vogue Terrace team considered that the BIPV expert was the BIPV laminate supplier. The BIPV laminate supplier believed that there was a BIPV system designer in another part of the project - who in fact did not exist. In contrast, the Future Green team saw the expert as the glazing supplier - who used the BIPV laminate supplier to validate the layouts, but who actually had no expertise in BIPV system design. In Synergy Court, the louvre supplier saw himself as the BIPV expert, recognising that the project needed one and that it was in his own interest to fulfil this role. Understanding his own limitations in knowledge, the louvre supplier then drafted in experts in BIPV laminate technology, micro-inverter technology and wiring technology to address these limitations. This understanding - that expertise has value, and that although it might come from different sources, it can be coordinated to deliver an integrated solution - served to give the louvre supplier a competitive advantage and provided clarity of decision-making.

This discussion shows both that team integration played a key part in the adoption of BIPV and that it is far from straightforward. The prior relationships between actors and the working relationships between actors heavily influenced the way that problems were anticipated and solved. The role of the systems integrator was often an informal role, but had a key impact on the team dynamics. The relationship of the team to BIPV affected the way that the team approached the design and installation of the BIPV system. Finally, the presence and locus of BIPV expertise shifted through the project team and often did not reside in one single team member. When it was both present and stable, it brought clarity and focus to the team and added value to the contract.

9.2.3 Integration of project processes

The final section on exploring integration is concerned with specific factors which emerged from a comparison of processes such as selection of the supply chain; definition of work packages; development of design criteria; and division of responsibilities during installation. Each of the case studies used the same stages as set out in design and build contracts, but each implemented them differently. Issues of prior commitment to certain service providers, timing of the involvement of certain providers and division of work package content resulted in significant differences in the outcome for each case.

The supply chain for Vogue Place has already been discussed. In terms of process, rather than appointing a contractor to design the PV system, the main contractor decided to buy the panels directly from the PV laminate suppler and “free issue” them to the façade contractor. This reinforced the separation between BIPV and the building façade and discouraged integration of these. In addition, the procurement process favoured by the main contractor was to delay issuing of tenders and contracts until as late as possible into the build, so that packages could be optimised for the best returns to the contractor. The façade contract was let early on in the project, but the wiring contract was one of the last packages to be defined - the building was almost watertight before the wiring system was designed. This led to problems in finalising the design of the façade brackets and very late decisions on wiring runs. The separation of the BIPV electrical contract led to a lack of integration of the BIPV system itself and with the building.

In the case of Future Green, there was no pre-determined supply chain, but the supplier of the BIPV glazing panels was fixed by the architect prior to tender. This made the selection of the façade supplier more likely because of an existing close working relationship between the façade supplier and the glazing supplier. Similar to Vogue Terrace, the early lock in of suppliers meant that experience of BIPV was lacking which subsequently reduced the level of integration of the BIPV system and the building. As soon as the main contractor at Synergy Court appointed the louvre supplier to provide a turn-key BIPV system, a new supply chain was set in train by the louvre supplier around the development of an innovative BIPV system which would deliver the generation target. It would appear that this new supply chain benefitted the implementation of BIPV more than the use of an existing supply chain, with its associated limitations.

The pre-tender and tender stages of construction projects involve the division of responsibility for elements of the building between suppliers through work package definition. The case studies highlighted different ways that work packages were defined, which affected the adoption of BIPV. In Vogue Terrace, the split between the visible part of the BIPV (the panels) and the invisible (the electrical element) was largely determined by the façade supplier, who declined to include the BIPV element within the façade contract. It is striking that in Future Green a similar split occurred between the visible and invisible element of the BIPV system, but in this instance the tender process meant that work packages were drawn up by an external M&E contractor and then awarded by the main contractor. The effect of this distribution of responsibility was that the M&E contractor loaded design portions into the work packages which were neither read by the tendering contractors, nor checked by the main contractor. This meant that the whole BIPV electrical system was left un-designed until installation and also led to a total lack of integration of the BIPV components.

A similar division of work packages might have arisen at Synergy Court, had there not been an issue with meeting generation targets. It was the insistence of the louvre supplier that there was a problem, and the subsequent awarding of the PCSO, which led to the BIPV system being awarded as a turn-key operation to the louvre supplier, thereby ensuring a high level of BIPV system and building integration. It would appear that whilst there is not necessarily one single best way to divide up work packages, a clear understanding of the interfaces and content of each package is needed if BIPV is to be successfully incorporated into a building.

Another project process which affected the adoption of BIPV was the development of the design criteria for the BIPV system. Although there was no specific electricity generation target for Vogue Terrace, the commitment to use PV technology gave an early focus to achieving some electricity generation. An outline BIPV system was developed by a design consultant well before tender, giving some degree of BIPV system integration from an early stage. In sharp contrast, the client and architect at Future Green adopted a sizing approach which was based on a minimum square meterage of panels rather than a specific generation target. The emphasis on square meterage focussed the design team’s attention on the visible aspect of the BIPV system, leaving the electrical part unconsidered. Synergy Court had a clear, negotiated generation target of 1% of the buildings energy usage. The target was challenging and focussed the design efforts around achieving it, thereby pulling the electrical and mechanical elements of the design into focus. The difference in the design criteria used on the projects also influenced the way the BIPV system was commissioned. Whilst all three projects required the BIPV laminate glass to be flash tested at the factory, only the louvre supplier at Synergy Court understood what these figures meant and how they compared to the design requirement. In Vogue Terrace the façade supplier insisted on an additional test on site to confirm that the units were operational before installation. Final commissioning was carried out by the wiring contractor who had no clear performance criteria to check against. The commissioning of the BIPV system at Future Green was carried out by the main contractor who turned the system on and checked that some electricity was being generated.

The commissioning process for Synergy Court was more complex, with an additional performance test being carried out at the louvre suppliers' factory to demonstrate the efficiency of the inverter system. This attention to performance, and the importance placed on meeting contract levels of output, ensured that the BIPV system and building were integrated. This discussion indicates that the design criteria used on each project had a major influence on the way that the technology was integrated into the building.

The variation in the way responsibilities were divided between contactors during the installation of the BIPV system was different in the case studies and affected how different elements of the BIPV system were integrated into the building. The façade supplier in Vogue Terrace viewed the BIPV technology as a source of risk in terms of damaging the integrity of the façade system. The façade supplier insisted that the BIPV brise-soleil panels were delivered to their factory where they were fitted into pre-fabricated frames. The BIPV units and the window units were packed into separate stillages and shipped to the construction site where they were assembled by the façade supplier's installation team just prior to erection. The BIPV units were fixed to the outside of the window units using pre-positioned brackets. The façade supplier would only guarantee the weather-proofness of the façade if the window units were fitted without the electrical wiring. The electrical contractor had to complete his work last and guarantee the integrity of coverings lifted and replaced during the electrical installation. This approach served to make the components of the BIPV system totally distinct and militated against both BIPV system and building integration.

In contrast, the façade supplier for Future Green arranged for the glazing supplier to ship the BIPV glazing units directly to site, where they would be installed by the façade supplier's fitters. This meant that the units arrived on site with freely dangling electrical leads which had not been designed into the frame and which had no pre-defined method of penetrating to the inside of the window frames. The resulting problem solving ultimately ensured that the BIPV units were integrated within the building, but largely as a retro-fit and with a three week delay in finishing of the internal fixings.

The installation of the BIPV assembly in Synergy Court was very different. The louvre supplier wished to be able to install all the louvres at his own pace and so developed a novel means of using the building BMU hoist to move louvres into position for a team of abseilers to install. This installation system meant that the dependence on the site hoist schedule was reduced to a few mass-liftings of louvres onto the roof into a stock-pile for the BMU hoist to position. The other notable difference in installation was the very clear communication between the louvre installer and the main electrical contractor and main contractor, making sure that boundaries of electrical work were clearly defined and anticipated. Both of these processes contributed considerably to the integration of the BIPV system within the building. It is clear from this analysis that procurement processes and design constraints influence the eventual installation outcome of the BIPV system. Echoing the comments in the integration of design processes, it would appear that regardless of how work packages or contracts are set up, integration at the time of installation needed flexibility from the electrical, façade and BIPV suppliers and this is made harder by a rigid application of the work package boundaries.

Two further factors which had an influence on the integration of the BIPV system and the building are the suppliers’ perception of risk from the technology and the effect of social artefacts. In the case of Vogue Terrace, the façade supplier perceived a risk to the façade integrity from the incorporation of BIPV and so excluded it from the façade package. This attitude to risk acted as a barrier for integration of the technology with the building. In the case of Synergy Court, the risk of not meeting the generation target acted as a driver for the louvre supplier to develop innovative solutions and integrate the BIPV system components.

In Future Green, problems of installing the PV panels, frames and wiring risked delays to the project schedule and this risk acted as an impulse for problem solving, rather than as a driver for innovation and integration. Similarly, the schedule considerations in Future Green and Vogue Terrace made the team take decisions which precluded bold and innovative choices, whilst in Synergy Court the need to meet generation targets over-rode schedule considerations and allowed for a PCSO to be issued and worked on. In addition, the schedule served as a foil against which to develop an innovative hoist system, so that integrated installation would not be unduly influenced by external considerations. A discussion of the effect of social artefacts will be developed further in section 9.3.1.

This cross case analysis demonstrates that integration cannot be characterised in simple terms, but is complex and includes elements of technological integration, team integration and process integration. Differences in the levels and types of integration of the case studies can explain the different project outcomes.

9.3 Dynamics of adoption: technological frames, decisions and co-development

The discussion above focussed on characterising the integration which occurred during the case studies and the way that these different types and levels of integration affected the adoption of BIPV. This section explores the dynamics of adoption in terms of the technological frames mobilised, the decisions taken and the types of co-development that took place within the case studies, and uses these to consider stabilisation mechanisms which fixed particular design features of both BIPV and the building.

The analysis earlier highlighted three types of co-development which occurred in each case study: lock-in; homogeneity of appearance; and mutual adjustment and adaptation, together with examples of innovation as the BIPV was integrated within the building. Each of these types of co-development followed from a series of decisions taken during problem solving during the projects. As described in the previous chapters, the three co-development types are:

- Lock-in: Where a decision is taken which sets or “locks in” particular features or characteristics of the technical system, which in turn force subsequent choices.
- Homogeneity of appearance: where aesthetic considerations and physical constraints of the building impose constraints on the BIPV system and vice versa.
- Mutual adjustment and adaptation of design: where the integration of the BIPV system and the building invite or force accommodations to each other.

These types of co-development and examples of each have been discussed in detail in previous chapters. The discussion which follows uses a comparison between projects to explore these types of co-development in more detail and to understand how the changing dominant technological frames influenced them.

Lock in

This type of co-development type often resulted from discrete decisions being taken as actors maintained a single dominant technological frame without seeing or understanding the frames of the other actors. Lock-in is evident in all three case studies, and is most evident at the start of each project. In Vogue Terrace, the client adopted the Risk Minimiser technological frame when taking the decision to retain the existing project team and did not anticipate any knock-on effects which might have been evident if the Design Optimiser frame had also been mobilised. This decision led to a lock-in of experience (or inexperience) with the technology, which in turn, led to the rejection of a turn-key BIPV package and a de-coupling between the BIPV system and the façade.

The client in Future Green mobilised the Cost Watcher frame to gain ERDF funding and this locked-in the use of PV technology. Later the client's desire for a visible statement of sustainability (Green Guardian frame) dominated the decision-making and locked-in the use of BIPV even though other less visible, cheaper technologies were available. The architect chose thin film technology whilst mobilising the Design Aesthete frame and this decision locked-in the sizing of widows and glazing panels. In Synergy Court the client's desire for the design to have four interconnected towers (User frame) locked-in the PV generation figure, whilst the new curved roof-shape (Design Aesthete) locked-in the available generation potential for the BIPV system.

In all of these examples, decisions were taken without reference to other technological frames or in opposition to other technological frames. The dominance of a single frame resulted in the co-development type of lock-in. In two cases, lock-in resulted in innovation - the louvre supplier in Synergy Court developed an innovative BIPV system using Q cells and micro-inverters, whilst the façade supplier in Vogue Terrace developed an innovative bracketry system to house the BIPV wiring. Lock-in can force a direction of design which may conflict with one or more of the frames of the project actors, thus forcing a design innovation to counter this.

Homogeneity of appearance

Homogeneity of appearance is different from lock-in and results in less innovation and rather more incremental adjustments. This type of co-development occurs where the appearance of the BIPV technology and the building are interconnected and a series of decisions are taken which influence the appearance of one or both of these. The decisions are often taken by actors mobilising two frames - that of the Design Aesthete and one other, often the Design

Optimiser. The clearest example of this in Future Green was when the architect mobilised the Design Aesthete frame to select thin film technology and the glazing supplier mobilised the Design Optimiser frame to suggest suitable glazing sizes. The architect was able to bring together these two frames to design windows which took into account limitations of the technology but which were also aesthetically acceptable. For Synergy Court, the blue PV cells within the BIPV louvres made the BIPV louvres conspicuous on the building roof, which was unacceptable to the architect (Design Aesthete frame). Grey PV cells were ruled out by the louvre supplier on grounds of reduced generation (Generation Maximiser frame) and the architect decided to match the technology and provide aesthetic homogeneity by adding a pattern of perforations to neighbouring non-BIPV roof louvres. In the case of Vogue Terrace, the architect worked with the design consultant to reduce the number of PV brise-soleil louvres (Cost Watcher) while still retaining an aesthetic balance of PV and non-PV louvres on the façade (Design Aesthete). This new layout meant that the layout of the building elevation was complicated by grouping of PV and non-PV units which later complicated wiring schemes. Unlike decisions shaped by lock in, these incremental adjustments to the building and BIPV system appeared to happen without many of the actors being aware of them, although the results of those decisions had major effects on the appearance of the building and in some cases the performance of the BIPV system.

Mutual adjustments and adaptations

Co-development by mutual adjustments and adaptations of both the BIPV system and the building describes a type of co-development which results from the physical intersection of the technology and the building and tends to follow an integrated decision-making mode, where different actors mobilising different technological frames come together to resolve problems. In this type of co-development the Design Optimiser frame was often dominant, but what is also noticeable was that the actors involved in the decision-making were able to see the problem through different technological frames and align these frames to find a solution. The process of arriving at a solution tended to be collaborative in nature and either gave rise to a "least-worst" option being adopted or resulted in innovation. In Vogue Terrace, the need to physically house the BIPV cables gave rise to an innovative channelling and bracketry solution with hidden cable ways and an integrated capping system. This allowed for the cables to be retro-fitted by the wiring contractor once the façade contracts had been completed. In Synergy Court, the need to lay the cables off as the louvres were installed led to the development of a series of collector box stations with plug-and-play junctions. Less beneficial examples point to more ad-hoc decisions taken to minimise the impact of schedules or risk, which caused unanticipated knock-on effects later in the project. In Vogue Terrace, the seemingly arbitrary decision by the PV laminate supplier to increase the laminate thickness by 1mm led to heavier bracketry design. This change in loading on the fixing bolts went unnoticed by the façade supplier and the bolts were not stiffened. Ultimately this resulted in distortion of the fixing bolts after installation. In Synergy Court, the timing of electrical contractor works led to the louvre supplier having to make assumptions about the locations of collector boxes and to over-estimate the lengths of cables "to be on the safe side". The same ad-hoc decision-making was evident in Future Green when the glazing units arrived on site and a way of accommodating the flying cables had to be found. Collaborative or integrated decision-making finally provided an acceptable way of drilling through the frames to get the cables inside the building, but this had a number of knock-on effects, including delays, re-work and risk to the water-tightness of the frames. There was little other evidence of this decision pathway in Future Green - possibly because the BIPV was only really seen as window panels and never seen as an integrated system.

This discussion shows that the co-development types of lock-in, homogeneity of appearance and mutual adjustments corresponded to different decision modes. Lock-in was seen to be associated with innovative or radical decision-making, allowing innovation to occur. The co-development mode of homogeneity of appearance gave rise to incremental decision-making which allowed discrete episodes of co-development to occur. Finally, the co-development modes addressing mutual adjustment gave rise to collaborative decision-making, which let co-development flow as the elements of the BIPV system and building influenced each other, sometimes resulting in innovation.

Within each case study analysis the role of the social artefact was evident in the process of co-development and the following section explores this interrelationship further.

9.3.1 **The role of social artefacts**

In all three cases social artefacts had a major effect on the co-development of the projects. In both Vogue Terrace and Synergy Court planning policy shaped the initial development of the schemes and the mutual constitution of the technology and building. The Merton Rule combined with the local planning strategy for building design drove the generation output target and the building shape for Synergy Court. In Vogue Terrace, the need for a sustainability strategy to achieve planning consent drove the decision to use photovoltaic technology on that project. Both of these resulted in the ultimate direction of the buildings. Future Green's use of PV technology was driven by meeting funding requirements rather than planning requirements, For both Future Green and Vogue Terrace the client decided that BIPV (rather than roof mounted PV panels) would give a statement of sustainability to the building, whilst for Synergy Court, the use of BIPV became fixed when the outline of the building roof became stabilised and roof mounted panels became impossible to fit.

Contract definition and work package specifications had major impacts on the co-development of the BIPV technology and the buildings. In Vogue Terrace the fixed procurement method constrained the content of the work packages. In Future Green the work packages and design portions defined artificial boundaries between the BIPV components and the building, which effectively held back co-development until the components arrived on site. In contrast, the tender documents used in Synergy Court served to drive a guarantee of output and put in train a series of co-developments which brought about an innovative and integrated project.

The project schedule was a third social artefact driving co-development, providing a point of consensus between actors as problems had to be solved to allow the project to proceed on time. With Vogue Terrace this allowed innovation in respect of the cableway design to be developed, and in a smaller way the installation schedule focussed the suppliers in Future Green to find a way to get the cables inside the frames in Future Green. The schedule constraints in Synergy Court drove the innovation of using the BMU hoist for the louvre installation.

Social artefacts can therefore be seen to be important factors in the co-development of the BIPV system and the building and can force lock-in or facilitate innovation. The case studies showed the influence of social artefacts in the decision-making process as they framed the technological view of the Cost Watchers, Time Sentries and Risk Minimisers. However further analysis of the effect and interrelationship of these social artefacts fell outside the scope of this research and further analysis and research would be needed to explore this area more.

9.4 Summary

This cross case analysis has explored key themes of integration and the dynamics of co-development and has highlighted some of the differences between the three cases. Integration cannot be characterised in simple terms, but is complex and includes elements of technological integration, team integration and process integration. The mobilisation of different technological frames by the project actors influenced the way decisions were taken in the projects and affected the co-development of the BIPV system and the building. Project processes (like work package specification and installation) and the role of social artefacts are not obvious influences, but both have been shown to affect the adoption of BIPV. The following chapter moves on to interpret the case study analysis and re-engage with the literature on innovation adoption, to address the specific research question of how the mutual articulation of a building and the technology develops as BIPV is incorporated within a building.

Chapter 10: Discussion

This research explored the micro-level dynamics surrounding the adoption of innovative technology in three buildings. The three case studies and the comparative analysis which followed showed that adoption of BIPV within a construction project is more than a single moment; rather it is a complex process around which much can be observed, but about which there has not been significant empirical enquiry or theoretical development.

The cross case analysis (Chapter 9) utilised two general themes to reflect on the data from each case study - integration and the dynamics of co-development. Examination of the integration process highlighted three distinct types of integration: technological integration; team integration; and process integration. Each gave different insights into the adoption process. Exploration of the dynamics of co-development showed three types of co-development - lock in, homogeneity of appearance, and mutual adjustment - each of which resulted from different ways of making decisions. Analysis of the co-development of the building and technology drew attention to the role of social artefacts in during the adoption of innovation.

This chapter moves from an analysis of the three specific cases to a re-engagement with the literature on the adoption of technology. The review and discussion in Chapters 2, 3 and 4 identified a broad range of literatures which are relevant for the understanding of the adoption of innovative technology. The review began by exploring research into the performance gap and showed that the adoption of innovation could not be accounted for by a purely technological view of adoption, and established a link with literature on the process of innovation. It went on to explore the adoption of innovation from the perspective of the process innovation approach and finished by linking six characteristics of innovation adoption from the process of innovation approach to themes of processes innovation within construction management literature at the level of buildings. The following discussion outlines the findings from the case studies and explores how these contribute to the previously discussed literatures. The chapter concludes with a reflection on the contribution of this study to research into the adoption of integrated technologies.

10.1 The complexity of innovation adoption: the contribution of the performance gap and the importance of the local context.

The case studies have shown that the adoption of BIPV cannot be contained within a single, simple model and is far more complex than a single stage in an innovation model would suggest. When considering integrated technologies, a better understanding of the mutual constitution of the technology and its context is needed.

This research has demonstrated that that BIPV technology is not only affected by its local context, but also shapes that context. Slaughter (1998) identified that system innovations were different from the four types of innovation developed by Henderson and Clark (1990). Slaughter (Slaughter, 2010a; Slaughter, 2010b) drew attention to the importance of understanding the commitment of resources needed to assist adoption and suggested that attention be paid at the initiation of the project to the implications of innovation on the project supply chain. The case studies reinforce Slaughter’s call for early consideration of innovation and its effect on adoption, but show that this is in tension with standard project stages and processes. In addition analysis of the case studies has shown that the performance of the assemblage of the innovation should be considered, rather than just its impact in the project process.

The literature review established that local planning requirements and building certification schemes like BREEAM may lead to unexpected consequences for the adoption of sustainable technology (Russell and Thomson, 2009; Schweber, 2014). The analysis of the case studies supported this view. Instead of adding clarity and focus to the adoption process, the effect of policy and certification was mixed. In two of the cases resulted in fragmented adoption, with BIPV systems being installed which did not make any significant contribution to electricity production. A surprising aspect of the three case studies was the lack of consistent design criteria for the BIPV systems. BREEAM and EPC certification required only a particular square meterage of panels for Future Green, whilst the requirements for Vogue Terrace were vague - only that renewable capability be included. In contrast, the challenging specific generation target of Synergy Court focussed the design efforts around achieving the required output, thus focussing attention on both the electrical and mechanical elements of the design to produce an efficient BIPV system which delivered the required output.

As these examples suggest, the relationship between adoption and planning and regulation is not simple. The case studies support observations that the requirements of certification schemes like BREEAM can sometimes obscure their original purpose of encouraging sustainable building (Schweber, 2013) and do not necessarily improve adoption. The availability of Feed-in-Tariffs for electricity generated by the BIPV systems did not have any effect on adoption in the case studies. Not one of the actors on any case study mentioned Feed-in-Tariffs at all, which would seem to contradict some authors (Lowe, 2007; Yang & Zou, 2015) who argue that Feed-in-Tariff and other financial incentives would increase adoption of green technologies by driving the delivery of efficient systems to maximise income from the electricity generated. This difference might be accounted for in part by the particular nature of commercial building projects where the client is very rarely responsible for post occupancy energy use.

The systemic nature of BIPV makes its adoption particularly challenging. The technology is comprised of different components which make up the BIPV system and relies on a process of component selection, matching and configuration to provide an electrical output. To a large extent, the efficiency of the BIPV system depends on the degree to which the components have been matched and configured (Chapter 2). The plethora of options for component choice and configuration allows unique solutions to be developed for each application, but also means that there is no single accepted convention in terms of component selection, matching and configuration. In terms of adoption, this lack of standardisation creates problems of understanding and communication across the project team.

The case studies showed how the bespoke nature of BIPV allowed for multiple configurations of design and appealed to users with multiple requirements. Vogue Terrace used BIPV brise-soleil to provide aesthetics and shading, Future Green used BIPV as glazing and to provide a visible statement of sustainability and Synergy Court used BIPV roof fins to generate electricity. It has been suggested that better design of components, both in terms of technical improvements to performance (Sozer & Elnimeiri, 2007), standardisation of interfaces (Pagliaro et al., 2010) and better reliability (Laird, 2009b) will facilitate adoption. However the bespoke nature of high end commercial buildings and the variety of ways in which BIPV is integrated into buildings makes these component focussed factors less useful in analysing adoption of BIPV.

In two of the three cases (Vogue Terrace and Future Green) the only BIPV systems design was carried out at the scoping stage of the project and this was only in very outline form -

establishing how many inverters would be needed and what square meterage of PV cells would be required. Before detail design could be undertaken (more than a year later), the project manager had split the BIPV system into its mechanical (PV cells and laminate) and electrical (wiring, inverters and control system) components, and the BIPV system was never designed as an integrated whole. Even if technological advances in individual components had been made, the team would still have had difficulties in matching components, optimising output and anticipating problems because of the way in which the projects are delivered. It is interesting to reflect that there is very little literature which focusses on designing efficient, integrated BIPV systems, and that the current focus on improving individual components can only go part of the way to facilitating adoption. Section 11.6 reflects on the importance of identifying integrating interfaces early in projects before work packages are assigned to ensure that the distribution of work packages reflects the demands of integrated technologies.

The literature review established that adoption of technology is not a simple, one-way process of adoption and that analysis of the “performance gap” (differences between design performance and achieved performance of technology) can be used to understand some of the difficulties involved (Gorse et al., 2012; Dainty et al., 2013; Fedoruk et al., 2015). Authors who discuss the performance gap assume that targets for technologies or innovation performance are clear and have been concerned with either technical robustness (Yang, 2015), correct installation of technologies (Gorse, 2012) or optimising construction processes (ZHC, 2014, Dainty et al., 2013). Analysis of the three case studies supported using the performance gap to understand adoption, demonstrating that misunderstandings about the technology and lack of clarity around design and performance targets affected adoption. Data from the case studies showed that this lack of clarity extended to the commissioning and testing of the BIPV system. Adoption was complicated in the case studies by confusing generation targets, ill-thought out commissioning procedures, and varying weather conditions over the period of commissioning.

It is particularly difficult to establish the output of BIPV systems other than in laboratory controlled conditions - electricity generation depends on ambient conditions and varies from day to day, season to season and year to year. A BIPV system commissioned in the summer months would have very different output figures for the same system commissioned in the winter. In the case studies commissioning generally took place, or was expected to take place, over the period of a few days and the time of year for commissioning varied. Only one of the BIPV systems (Synergy Court) was installed with any form of on-line performance monitoring software. The other two case studies just had on/off lights on the inverters and a built-in display on the export meter showing instantaneous output and accumulated generation. Both the inverters and export meters in Vogue Terrace and Future Green were hidden, either on the roof or within the building, and were not part of the BMS system.

Although indirectly connected to the process of adoption, these points contribute to research on performance gap by showing that the process of understanding performance gap is not as simple as “just” measuring achieved results against predicted values. Neither the target generation figure nor the way of measuring achieved performance is straightforward. In research little attention has been paid to the initial lack of target generation figures on projects and to the difficulty of measuring the achieved output - over what period and by whom.

In addition to issues with performance gap and system design, BIPV has to be integrated within the multiple elements of a building and so is a “system within a system”. The case studies showed that this two-fold nature of BIPV proved challenging both in terms of system design and for its incorporation in construction projects. The bespoke character of BIPV would suggest that the BIPV system and the building would be designed together. However, the data did not support this and pointed to an independence of design which often came together only at the point at which the technology was integrated within the building. This demonstrated that the integrated characteristics of the BIPV technology were often obscured, as the technology was treated as a series of components which had to be accommodated within the building. For example the inverters needed to be housed on the roof of Vogue Terrace, the wires from the windows in Future Green had to be drawn into the building and the frames of Vogue Terrace has to accommodate the BIPV wiring. What was missing in two of the three case studies (Vogue Terrace and Future Green) was firstly, recognition and understanding of the integrated nature of BIPV and second, any one individual who both understood the nature of the technology and championed it. This observation contrasts with literature on innovation leadership which focusses on the importance of the role of innovation champions in driving innovation through an organisation (Nam & Tatum, 1997; Gambatese & Hallowell, 2011), but which does not identify the need to consider the nature of the innovation itself. Section 10.3.4 expands on this link to leadership in innovation literature. In many ways these observations on the lack of front end design of integrated systems applies to all the systems in the building or which form part of the building and this highlights the complexity of modern buildings, the increased challenges for the designers and their difficult task of spinning many plates at one time.

10.2 Processual view of innovation adoption

Process innovation research analysed innovation adoption in terms of a number of social patterns (Van de Ven et al. 1989) but analysis of the case studies has given a view of the adoption process which includes the dynamic relationship between the materiality of the technology and the building, and the social interactions of the project team. Findings have shown that although process innovation research is primarily considered in terms of developing tools for managers of innovation, the approach can be used to frame innovation adoption as a more socio-technical process.

10.3 Adoption of innovation in the context of construction projects

A second key contribution of this study concerns the specificity of construction projects as a context for technology adoption. The study draws attention to the limitations that standard project procurement processes place on the adoption of technology.

10.3.1 **The nature of construction projects and implications for adoption of BIPV**

Turning to the dynamic nature of the adoption process, the literature review established that there is a link between the integrated nature of technological innovation and an ongoing process of accommodation as the technology is incorporated into its local context. The preceding sections have outlined the characteristics of both BIPV and construction projects and shown how they influence adoption. It is perhaps implicit that the coming together of these complex systems of components multiplies the issues and complications in shaping adoption. It is therefore too simplistic to consider the building as a simple fixed system into which BIPV fits. A building comprises many systems (HVAC, lighting, electrical supply, services etc.) which are all brought together through project management. BIPV is just one of those interrelated systems, but brings particular challenges because its performance is dictated by the building configuration. What is clear in the case studies was that the points of friction - where the interconnectedness of the BIPV system and other parts of the building occurred - were not apparent from the outset of the project, but were stumbled upon at unexpected points as the projects proceeded, often coming as a surprise to the project team.

In terms of the research question posed at the start, it is clear that adoption of new technology is a complex process which results in a three-way mutual articulation of the BIPV system, the building and the project team which manages the process. Analysis of the case studies has shown that three different types of co-development of the BIPV system and the building occurred and that the way that technological frames were mobilised by the actors determined how decisions were made during the projects and how these co-development types came about. Integrated decision-making occurred when actors had the flexibility and awareness to mobilise multiple technological frames and often resulted in the development of innovative solutions which simplified adoption. On the other hand, actors making limited use of technological frames made more discrete decisions, without reference to the effects of the decisions on either the BIPV system itself or on the building, and these decisions resulted in a rather disjointed and ad-hoc adoption process.

The case studies supported the view that the complexity of construction projects masks instances of innovation as projects proceed (Winch, 2003; Reichstein et al., 2005; Harty, 2008). There were many examples of innovation in the case studies. The louvre supplier at Synergy Court advocated the use of micro inverters, the façade supplier and glazing supplier for Future Green worked out how to accommodate frames and wiring, and the architect for Vogue Terrace experimented with a white interlayer on the BIPV louvres. These examples from the case studies support Winch (2003) in his assertion that the construction sector does adopt innovation and they point to many examples of discrete adoption happening at different times within a project. The challenge for construction is to bring these discrete innovations into view and use integrated decision-making to facilitate adoption of innovation.

10.3.2 The management of projects, change and decisions

Project Processes and Procedures

This section focusses the discussion on the mechanics of project work in terms of project processes. This draws attention to the limitations that standard project procurement processes place on the adoption of technology.

The literature review established that ideals of project management include timely work package definition and tender, increased collaboration and continuity, and a fixed project schedule (Cooke-Davis, 2002). These particular ways of working did not support the adoption of BIPV and analysis of the case studies explored the tension between these ideals of project management practice within the industry and the adoption of innovative technology.

Conventional mechanical and electrical demarcations created artificial barriers between parts of the BIPV system. Another negative effect of standard project practice was the joining and leaving of project actors throughout the project. In Vogue Terrace the main contractor involved in the initial design phase was a different person to the main contractor responsible for managing the detail design and construction stages, and the façade supplier at the tender stage was a different person to the façade supplier responsible for delivering the design. Changing project personnel as a result of standard Design and Build practices meant that the rationale or history behind decisions was lost and knowledge was siloed amongst project team members.

The analysis of the case studies drew attention to the relationship between standard construction project procurement processes and the adoption of BIPV. All three case study projects were based on Design and Build contracts with clear project stages and processes. In two of the case studies these standard processes - of developing work packages and selecting firms to tender - had a negative effect on the design and integration of the BIPV system into the building. Early division of design work between mechanical and electrical disciplines, and the very early development of work packages before detail BIPV system design had taken place, made it difficult to integrate all the elements of the BIPV system and for an assessment of the whole BIPV system performance to take place. Similarly, the process of tender and awarding of contracts relied on previous relationships and understanding affected the ability of the contractor to deliver the work package, in one case resulting in a redrafting of the work package to suit the expertise of the contractor. These practical findings contrast to more theoretically based literature on the awarding of contracts in construction projects which tends to focus on construction project management and law (Clough et al., 2000; Murdoch & Hughes, 2002), risk allocation (Loosemore & McCarthy, 2008), or analysis of delay and dispute (Fenn et al., 1997). The effect of issuing the contracts for the BIPV was evident at the design and installation stage, where the siloed way of working within work packages created artificial boundaries between parts of the BIPV system and the building. Façade installers did not consider the way that wires would penetrate the façade until close to installation and the siting of cable runs and inverters was not considered by the main contractor until the main electrical work was carried out. It would seem that the contracts generated artificial boundaries between the contracts which were not picked up by the project design coordinator role. These artificial boundaries became evident at points of friction, where different parts of the BIPV system intersected with each other or with other parts of the building.

One additional tension between project stages and adoption is illustrated by the unwillingness of suppliers to engage heavily in projects before contracts are signed. This reluctance springs from the fear that they will give away their specialised knowledge without gaining the contract. In Vogue Terrace the PV laminate supplier did not engage fully with the architect before contracts were signed and in Synergy Court it was only the PCSO that allowed the louvre supplier to design the BIPV system. It appeared that the standard project processes discouraged suppliers from putting detailed design of the BIPV system into the early stages of the project because of the uncertainty of winning tenders and potentially giving information to competitors. These findings add a more practical element to construction literature on pre-tender design which focusses on the gap between pre-tender and post tender design by researching the accuracy of pre-tender cost estimates (Skitmore & Picken, 2000, McCaffer et al., 1984) or the study of post contract award design changes (Cox et al., 1999).

This use of contracts to guard against risk rather than to enable the project is highlighted by Sage et al (2010) and the empirical evidence from two of the case studies supports this observation. In Vogue Terrace the façade contractor privileged risk to the façade integrity over supply of an integrated BIPV system; in Future Green the electrical design portion for BIPV was put into the main M&E contract so that inadequacies of early design were passed along the supply chain. Challenging the status quo and changing the way that work packages were allocated only occurred in one of the case studies (Synergy Court) when the louvre supplier identified a risk of not meeting generation targets. It was the insistence of the louvre supplier that there was a problem, and the subsequent awarding of the pre-contract design order (PCSO), which led to the BIPV system being awarded as a turn-key operation to the louvre supplier, thereby ensuring a high level of system and building integration. Slaughter (Slaughter, 2010a; Slaughter, 2010b) drew attention to the importance of understanding the commitment of resources needed to assist adoption and suggested that attention be paid at the initiation of the project to the implications of innovation on the project supply chain. The case studies reinforce Slaughter's call for early consideration of innovation and its effect on adoption, but show that this is in tension with standard project stages and processes.

The final part of this section considers two issues, both related to contracts: content of the work package contract, and the effect of the contract on the eventual BIPV system performance. Gruneberg et al.'s (2007) suggestion that performance-based contracting (PBC) could ensure that operational benefits of integrated technologies are achieved and might facilitate the process of adoption is supported by the analysis. In two of the case studies there were differences between what was specified in the work package by the main contractor (or his agent), what was put into the tender document by the supplier, and what was delivered at installation. In Future Green the main contractor asked the M&E consultant to draw up the work packages for both the electrical and mechanical parts of the BIPV system. The electrical work package contained a substantial design portion clause, but the package detail was not read by the main contractor prior to being given out to tender. The supplier submitted the tender back to the main contractor, but had not read the requirement for the design portion. The main contractor awarded the contract but was not aware of the detail requested in the original call for tender, or its omission that from the tender bid. The supplier did not carry out the design portion and consequently the electrical system was not designed and the inverter was not ordered. The only time the contracts were examined was when the design omission was noticed at installation.

None of the case studies had contractual arrangements in place for final commissioning of the BIPV system and the monitoring of its performance. Future Green had an on/off method of commissioning that did not require any performance data from the BIPV system. Vogue Terrace had not defined a commissioning schedule and at Synergy Court the louvre supplier was to have completed installation and moved off site long before the commissioning of the

BIPV system was to occur. These examples illustrate some limitations of current contractual arrangements and indicate that changes to these processes should be considered when integrated technologies are specified on projects.

It is clear from the analysis of the case studies that the procurement process influenced the eventual installation outcome of the BIPV system and that the current system of commissioning contracts did not support optimisation of BIPV system performance.

Change Management

In construction literature change management is largely analysed in terms of a hindrance to projects in terms of cost over runs and reduced project efficiency (Love et al., 2002; Joskow & Rose, 1985). The case study analysis in this research appears to support a more positive interpretation of change and the potential upsides to deviations from the original project specification (Shipton et al., 2014). Given the long lead times of construction projects, rapid technological changes of components in the BIPV system occurred as the projects proceeded. These technological developments made a contribution to the efficiencies and outputs of the BIPV system and in some cases made it possible for the system to operate at all. In Vogue Terrace, advances in wiring technology and inverters made it possible to fit the BIPV wires into the brise-soleil frames and site the inverters on the roof. In Synergy Court, the use of micro inverters meant that the generation targets could be met. It could be argued that flexibility to adopt technological innovations positively enabled progress, rather than being a herald of inefficiency and poor management.

Decision making

Analysis from the three case studies highlights the influence that types of decision-making had on the adoption of BIPV and on the type of innovation itself. Integrated decision-making in Synergy Court led to a radical innovation in terms of the adoption of a micro-inverter system. The discrete decisions made in Future Green resulted in very neatly spaced PV cells which obscured the view from the windows and which generated very little electricity. Larsen (2005) explored how different concepts of adoption resonated with the empirical data at different stages within a project and this appears to be mirrored in the different types of decision-making at different stages within the case studies. In the case of Future Green, the integrated decision-making 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. However, 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 resulted from this decision. The main contractor’s use of the discrete decision-making mode in deciding work package allocations set the scene for the fragmented development of the BIPV system and a series of problems at the interfaces of both the BIPV system and the contractors. The integrated decision-making mode helped to address the local issues on site, and encouraged innovative problem solving. However, it could not alter the effect of the earlier discrete decision-making mode, which had locked-in opaque windows and low generation outputs from an early stage for the project.

From the discussion of the literature on decision making in Chapter 3, it is clear that despite research which acknowledges the need to understand decision making which occurs in complex project networks (Taylor & Levitt, 2007), there is a paucity of empirical research which looks at the effects of decision making on the technical innovation itself. This empirical research of the adoption of BIPV shows that as well as the need to recognise the key roles of individuals within project networks (Keast & Hampson, 2007b) and the complexity of communication within projects (Chinowsky et al., 2008; Bakht & El-Diraby, 2015), that different decision modes directly affect both the performance of the technology and subsequent chains of decisions making.

The understanding of the decision-making modes and the resulting co-development of the building and BIPV also contributes to research on the dynamics of innovation in projects, and to the discussion of innovation types and their effects. Garud and Karnoe (2003) explored the idea of decision pathways being divided between breakthrough and bricolage, postulating that continual development of ideas (bricolage) was more likely to support innovation over the longer term than a series of jumps in technological solutions (breakthrough). The findings from this research suggest that the mutual articulation of the building and BIPV is a form of bricolage and that different types of co-development support different types of innovation.

Analysis of the three case studies has shown that innovation occurred during co-development of the BIPV system and the building, and was often the result of a need to solve problems associated with lock-in. Innovation was almost always associated with a coming together of experts to address the problem, which resulted in the exchange of views and the development of new solutions. In the context of the adoption of BIPV it is sometimes difficult to judge when an innovation is just that, and not merely a development. Although not a new question (it has been much debated in wider innovation literature (Ruttan, 1959; Sexton and Barrett, 2003)), this distinction can blur the recognition that innovation occurred in each case study. The preceding analysis adds to the empirical evidence that innovation does not stop at adoption (Fleck, 1988; Williams and Edge, 1996), but continues as the BIPV system is incorporated into the building

10.3.3 **Shifting performance criteria**

The empirical evidence from the three case studies clearly shows that shifting performance criteria for the project actors have an important impact on the adoption of technology. Use of SCOT and the identification of technological frames highlighted the way in which project actors used different criteria to assess the technology and to make decisions at different times of the project. Process innovation research showed how criteria shift in a project in terms of different interests of project personnel (Van de Ven et al., 1989), but the case study findings show that these different perspectives are not contained within individual roles, but are taken up and then dropped by each actor at different times in the project. The issue that this observation raises is how to establish the visibility of criteria associated with the innovation's performance, rather than the more obvious goals of project delivery and cost.

10.3.4 **Leadership of innovation**

The need for increased capability and support for innovation adoption (Utterback & Abernathy, 1975; Heinstein et al., 2013) is easy to see, but analysis of the data highlights the distributed nature of knowledge across many actors (for example architect, M&E designer, suppliers and main contractor). Each had a role to play in the design and adoption of BIPV, but their knowledge and capabilities about the technology varied widely.

This observation about the distributed nature of knowledge about BIPV amongst the project team introduces the role of innovation champion. The literature review established that the role of a champion to push through adoption of an innovation was important, but that opinion was divided over whether the role should be located within the project team (Nam & Tatum, 1997) or within the client organisation (Gambatese & Hallowell, 2011). This research shows that in each case study, rather than there being a single innovation champion, there was an informal role of BIPV systems integrator. This term refers to the actor concerned with developing the BIPV system as a whole and resided in a different location within the project, shifted between project actors and came to the fore at different stages of the project.

Building on the idea that the systems integrator is a shifting, informal role within a project team, it also follows that there does not have to be a single BIPV champion watching over the successful integration of the BIPV system. Rather than having one champion who pushes the innovation's adoption (Gambatese & Hallowell, 2011), the observations from the case studies suggest that innovation adoption relied on multiple actors informally taking up the challenge at different times. The actor assuming the role of systems integrator took ownership for bringing together actors responsible for particular aspects of the BIPV system or building design and resolving problems in the project. The other project team actors perceived that the systems integrator was now an "expert" who had the requisite knowledge to guide decision-making and so they had no need to develop an understanding of the BIPV system themselves. As the person fulfilling the task of systems integrator changed through the projects, so did the perceived locus of expertise and so responsibility for the BIPV system design moved through the project team without anyone actually formally assuming responsibility. In this way, by the end of two of the case studies the BIPV systems had been implemented without ever having been designed.

10.3.5 **The temporary and evolving nature of project teams**

Process Innovation research has pointed to both the issue of evolving project teams and to the possible negative effects in terms of loss of knowledge and relationships (Angle & Van de Ven, 1989). The SCOT analysis of the case studies allows clear interpretation of the effect on the building, technology and project team as new actors become involved with the project. Other parts of the discussion have highlighted issues of continuity and collaboration, but in summary the effects can have positive outcomes in terms of allowing new knowledge and solutions to be included.

10.3.6 **Managing the supply chain**

The literature review established that the supply chain of a construction project has a complicated series of relationships and obligations which are typically bound through complex contractual arrangements (Sinclair, 2012). Within the formal systemic arrangements and interdependencies, there are informal systems, relationships and procedures which further complicate adoption. The following section discusses the dynamics of adoption across the supply chain and the challenges of integration.

Each case study had a different way of allocating responsibility: both formally (through project processes); and informally (through informal alliances or with mechanisms like the systems integrator). The dynamics at work across the supply chain could be considered using the concept of relative boundedness (Harty, 2010), which recognised that the envisaged outcome of an innovation is often different to the result achieved and that these differences can to some extent be accounted for by the varying degrees of interdependence within the supply chain. The case studies provide insights into additional ways that relative boundedness might be considered, by showing that standard project processes themselves may bound decision-making and change the outcome of an innovation. An illustration of this is that in Vogue Terrace the tender process was bounded - it was tightly defined and controlled by the project manager - and this set the direction for the de-coupling of the mechanical and electrical elements of the installation. In the case of Synergy Court, the planning process imposed a bounded decision-making process which locked-in the generation targets and set the direction of subsequent co-development. Harty recognised the complexity of the adoption process in construction projects and called for the collection of more empirical evidence. This research provides some of that evidence and demonstrates how the interdependencies between technological innovation and its context come together to shape both the technology and the building.

The case studies contradicted the idea that close working relationships and integrated processes and procedures aid the adoption of innovation (Egan, 1998; Wolstenholme, 2009). The BIPV case studies illustrated some negative effects on the supply chain of long-term relationships, collaborations and alliances. In Vogue Terrace the previous relationship between the main contractor and the façade supplier seemed to give the façade supplier an “easy pass” to decline to include the BIPV system within his work package. In Future Green, the easy working relationship between the façade supplier and the glazing supplier allowed design difficulties to be glossed over without being addressed, and the past collaboration between the architect and glazing supplier made the architect accepting of the new technology without questioning its effect. It was only in Synergy Court, where the louvre supplier insisted on changing the status quo by supplying a turn-key BIPV system, that a new supply chain was formed which delivered an innovative design.

What was clear in the case studies was that previous good working relationships between contractors prevented the identification of problems early in the project and this resulted in a degree of unintended collusion to fix issues quickly, rather than to appreciate the overall impact of decisions. These findings mirror authors who have highlighted two issues which challenge supply chain integration: the reliance of collaborative projects on informal relationships within the supply chain (Bresnen & Marshall, 2000a); and the propensity of principal contractors and clients to form longer-term relationships with each other rather than with subcontractors (Briscoe & Dainty, 2005). In the case studies it was the formation of new relationships within a supply chain which served the adoption of BIPV better than established ones.

10.4 Implications for adoption of BIPV and other sustainable technologies

The previous sections have discussed the impact of the fragmented and systemic nature of construction projects on adoption and have highlighted the complexities that these characteristics have on the dynamics of adoption in projects, the complications of supply chain in adoption and the effect on adoption of project practices, process and procedures. The findings above support a number of points which extend to the adoption of other renewable technologies in general.

A number of aspects of the BIPV system posed challenges in construction projects. These included: the failure to appreciate the integrated nature of the technology; the tendency of the building project team to privilege visible aspects of the BIPV system over the electrical system; and the implications of initial design decisions for the incorporation and generation potential of the technology. The analysis has highlighted the way in which failure to anticipate and plan for the effect of particular decisions on other aspects of the interdependent systems posed problems for the team and potentially compromised initial technical and design goals. Greater awareness of the challenges which BIPV posed would have allowed for better planning and fewer unintended consequences.

The case of BIPV directly challenges a number of basic assumptions which inform research into innovation in general and sustainable innovation in particular. In much of the literature, innovation, product development, commercialisation and adoption are treated as distinct stages in a linear process (e.g. Rothwell, 1994). Although both social and technical aspects of a technology influence adoption (Lees & Sexton, 2013), they are often treated as radically distinct, with researchers focusing on one or the other. Finally, technology as products are depicted as uniform, standardized, stable physical artefacts with a clear manufacturer and expert knowledge (Jelle & Breivik, 2012).

BIPV challenges all of these assumptions. The bespoke systems characteristics of BIPV and the local context into which it is incorporated means that innovation and product development continue well into commercialisation and adoption. Similarly, in the case of BIPV considerable innovation and development occurs on site as construction of the building unfolds. Finally, in the case of BIPV, there is no single product and there is no BIPV expert. Instead, BIPV expertise resides in diffuse pools of different types of knowledge and these silos very rarely come together in cohesive product development or design efforts.

These observations pose important challenges for the adoption and upscaling of BIPV. Key issues include product standardisation and the integration of the building process. In the UK, as long as commercial construction remains a bespoke sector, BIPV can be expected to retain its bespoke character. That said, the variety of motivations for using the technology and requirements are not infinite. One way forward might be to develop a suite of BIPV systems to respond to different types of customer and building needs (for example, developing options for high generation potential, aesthetic high transparency applications, and integrated façade panels), accompanied by much clearer communication of the technical issues involved as well as of the trade-offs between different considerations.

It is helpful to reflect on whether BIPV is an exceptional case or whether it highlights features common to other sustainable technologies. Whilst possibly extreme in its bespoke systems character, the examples of ground source heat pumps and district heating systems suggest that it is far from unique (Holden & Abhilash, 2014). The technical complexity of the system means that:

- clients and developers tend to focus on the visible features of the system;
- innovation continues well into adoption;
- its incorporation spreads across multiple work packages, often at the expense of standard contractual structures and procedures.

The use of this type of socio-technical analysis in the consideration of other sustainable innovations would demonstrate the integrated and socio-technical nature of the technology and would allow the debate on product development of sustainable innovations to move forward. It is only once a more dynamic understanding of innovation adoption is applied that a clearer view of the nature of integrated sustainable innovation can be developed.

10.5 The application, contributions and limitations of the SCOT approach

The final part of this discussion focusses on the application, contributions and limitations of SCOT as an analytical approach in this research. The section reflects on the challenges of operationalising the approach and then goes on to identify the contributions and limitations of the approach in this research. Section 10.5.2 identifies how the approach brought the dynamics of adoption into focus, allowed an understanding of how decisions are made and demonstrated the effects of those decisions on both the artefacts and the actors. The section finishes by reviewing some limitations of the approach which were established during the analysis of this research.

10.5.1 **Reflections on using the approach**

Although a seemingly simple approach, its application proved to be surprisingly labyrinthine and fraught with complexity. SCOT is a micro-level approach which relies on interviews and documents to generate information – much information! The SCOT diagrams appear simple – with only four concepts to map (artefact, technological frame, problem and solution) - but there is no toolkit for deriving a mapping of the development of the assemblage. In practice dilemmas about which information to include, how to map the changing constituencies of the technological frames, seeing the validity of groupings and logics and linking different phases of the projects made the approach troublesome. Considerable thought and consideration was needed to establish ways of communicating the case studies. Co-development diagrams were invented and developed to summarise the different streams of development. A0 sized SCOT diagrams were drawn to develop an over-view of the project to link phases and the varying accounts of actors, and drawings were annotated with boxes which identified which actors were in each technological frame at each point of decision making. An additional challenge in terms of construction projects was to map the shifting composition of technological frames as the project moved through the different project stages (from concept to construction) and to capture the dynamic nature of these changes.

The challenges of operationalising the approach were considerable, but the very clear concepts of artefact, technological frame, problems and solutions were also strengths. By having this concept clarity, it was possible to keep the important things in mind and to pay attention to the unfolding nature of adoption and its implications on the artefacts, assemblages and actors. The diagrams allowed the story to be told through the multiple interviews and allowed for different threads of the stories to be taken up and followed to their conclusions.

10.5.2 Contributions of the SCOT approach

The preceding section reflected on how the SCOT approach was operationalised and outlined some of the strengths of the approach in this research. During the analysis of data three particular contributions of the approach became clear.

Dominant Frames

The SCOT approach is used to address how technology develops though a series of decisions taken by actors to address problems. The actors are involved in different ways according to their beliefs or frames. Despite a shift in project management literature from problem solving to problem structuring (and the development of a soft skills approach) (Crawford et al., 2006; Dainty et al., 2003; Olson et al., 2001), most scholars assume that actors with the same job title share the same views and prioritise similar issues. For example, project managers are depicted as prioritising efficiency, engineers prioritise functionality and architects are concerned with aesthetics. The SCOT approach demonstrated that this is too simplistic and that in fact groups coalesce around interests which transcend simple job titles. An example of this in the case studies was the Generation Maximiser group which comprised of architects, designers, planners and engineers. Membership of groups within the projects shifted and changed with rhythms that sometimes followed the standard project stages (initial design, tender, detail design etc.) but sometimes followed a different pattern. This change in membership supports construction and project management research which identifies different patterns of cooperation between project team members at different times within a project (Olson et al., 2001). At various times in the project the dominance of some groups was amplified by project stages (for example Design Optimisers dominated the solution of problems at the detail design stage). However at other times the dominance came from a source which was not obvious and which then disappeared, making the logic of decisions harder to follow. An example of this is when decisions were taken that seemed to follow from an unwillingness to engage with the technology but were actually based on a desire to minimise risk. These findings support research which moves away from the study of problem solving in favour of exploring the way that different project actors bring different perspectives to problem solving (problem structuring) (Franco et al., 2004) and makes a new contribution in highlighting the way that these perspectives shift during the project. Using SCOT to map out these project dynamics helped to draw out an understanding of the process of adoption.

Crossing the boundaries of standard project stages

One other major contribution of the approach was to deconstruct the standard project stages and to explore what occurred within each episode and how actors' different interests waxed and waned through the project. These findings are in tension with models of project management which show a linear progression of project stages and clearly defined stage gates (Cooke-Davis, 2002; Phillips, 2008). The analysis showed that the composition of groups sharing the same technological frame changed over the duration of the project, with actors joining and leaving at certain times and with some frames dominating at certain times within the project. The surprising absence of a group being concerned with generation maximisation shows that it is not always the seemingly obvious groups which dominate decision-making and shape the technology.

This insight into construction and project management contributes directly to literature which develops the themes of soft skills needed to manage projects (Dainty et al., 2003; Olson et al., 2001; Crawford et al., 2006) and allows project teams to have a better understanding of the dynamics occurring within the team. It is clear that SCOT allowed for a fine-grained exploration of the dynamics of each case, showing how actors become involved in different ways with different interests and how the technology developed through a process of negotiation to stabilisation.

Case Study Comparison

A classic use of the SCOT approach is to explore how an artefact arrived at technical stabilisation over a period of time. In a similar way to the comparison methods used in process innovation approach (Van de Ven et al., 1989), the case study comparison has highlighted similar patterns in the adoption process across the three case studies. The case study comparison of this research has provided a template to explore the detail of the front-end design of a construction project which is a departure from the standard problematic addressed by SCOT research. The comparison also gives a new perspective to project management knowledge about the micro-dynamics and their effects in construction literature. This is in contrast to more theoretical models of stage gate management (Ajamian & Koen, 2002), fuzzy front end design protocols (Kagioglu et al., 1999) and problem structuring (Franco et al., 2004).

10.5.3 **Limitations of the approach**

As the analysis of the data using the SCOT approach continued three particular areas of difficulty became evident. These limitations centred around the concepts of stabilisation and closure, the nature of artefacts and issues around the development of technological frames.

Stabilisation and closure

The analysis of decision-making within the case studies built on the idea of stabilisation and closure outlined in the SCOT approach (Chapter 4). Stabilisation is used to describe the process by which the design of artefacts becomes more fixed, whilst closure refers to the mechanism by which the interpretive flexibility between groups decreases through negotiation and conflict (Bijker et al., 2012). The processes of stabilisation and mechanisms of closure have been acknowledged by Bijker (2009) to be under developed, but two closure mechanisms have been identified as part of the approach: “Rhetorical closure” occurs when social groups see the problem as being solved and the problem effectively disappears. A second mechanism - “redefinition of the problem” - occurs when the solution to a new problem and overrides other considerations. This research was concerned with identifying how the building assemblage and technology reached stabilisation and closure, but the formal SCOT approach gave very little guidance on how to establish these mechanisms. Given the number of decisions taken and the complexity of cause and effect, it was difficult to establish precise processes and mechanisms. However this research did find empirical evidence for the two concepts. By identifying discrete and integrated decision making modes as processes of stabilisation it was possible to identify the ensuing path of problems and solutions which gave rise to closure. The two mechanisms of rhetorical closure and redefinition of the problem were found, however it was not possible to link particular processes of stabilisation to particular mechanisms of closure. Rhetorical closure was instanced in Vogue Terrace by the development of a solution of cableways to satisfy aesthetic and technical concerns, although this solution actually masked the problem of the BIPV system being effectively bolted onto the project. Redefinition of the problem occurred in Synergy Court, where the need to achieve generation targets - which was understood by actors in each technological frame - overrode other considerations of cost or risk, with the use of innovative micro-inverters being seen by the groups as the only solution. It would seem that the co-development type had some bearing on the mechanism of closure. Co-development by mutual adjustment gave rise to rhetorical closure where the assemblages were adjusted until the actors in each technological frame were satisfied, whilst co-development by lock-in gave rise to redefinition of the problem - where a need for the solution of a problem overrides other considerations. The identification of decision-making modes and types of co-development as stabilisation and closure mechanisms contributes to the operationalisation of the approach, but the relationship between these two concepts remains elusive.

The nature of artefacts

The artefact is one of the basic concepts of the SCOT approach, but the term is ambiguously treated. Artefacts are considered to be both single items of technology and assemblages of multiple items. In either event, the approach assumes artefacts to be easily identified and to maintain their identity throughout the process. As the project progressed, some artefacts took on different significance and their meaning within the project team changed. For example, in Vogue Terrace the brackets to secure the BIPV panels began as simple, functional brackets, but became a point of integration for the technology and the building and by the end of the project were a key component of innovation. It became difficult to identify if it was the artefact itself that was important, or its function – in the case above, the bracket was both a fixing mechanism and a way of carrying cables. This unfolding redefinition of artefacts made the use of the SCOT approach slightly problematic as different technological frames were applied to the artefact by the different actors as its meaning and significance changed. This made it difficult to maintain consistency of in parts of the analysis.

SCOT generally considers artefacts as the pieces of technology which are developed, but in these case studies some social artefacts like schedules and contracts had an equal if not greater role in the stabilisation and closure of the technological system. These social artefacts were identified during the analysis of dominant frames and were operationalised through the technological frames. The Time Sentry frame was essentially constructed around the various schedules and the Risk Minimiser frame was constructed around contracts. One last observation was that of conflict between the physical artefacts and the social artefacts such as schedules and contracts. The contract work packages in both Future Green and Vogue Terrace divided the BIPV system and made its integration problematic, whilst in Synergy Court the conflict between the lifting schedule of the site and the installation schedule of the louvres was resolved by the development of the BMS hoist system to allow for local manipulation of the louvres. Using SCOT to operationalise social artefacts was not straight-forward and is an area where SCOT was less able to provide an understanding of the dynamics of decision-making.

Relevant Social Groups, Technological Frames and SCOT

The technological frame is one of the key analytical constructs of the SCOT approach and has been used in this research in line with Bijker's outline (Bijker, 1999). During the analysis of the case studies it became clear that the technological frame remains a somewhat ambiguous concept particularly in relationship to social artefacts such as contracts and risk. Technological frames were introduced by Bijker et al in response to concerns about how power between groups can be represented and understood (semiotic theories of power) (Bijker et al., 2012;. Klein & Kleinman, 2002), but from the case studies it seems that actors can invest artefacts with power which is not necessarily obvious to themselves. This makes analysis of the decision-making motivations and processes in the design process more complex than the SCOT approach would suggest.

Chapter 11: Conclusion

The aim of this research is to explore the micro-dynamics around the adoption of innovative technology in three commercial buildings and so develop an understanding of what happens when innovative, integrated technologies are incorporated into building projects.

The research uses building integrated photovoltaic technology (BIPV) as an example of an integrated technology and examines what happened as BIPV was incorporated into three commercial buildings. It is concerned with the micro-level occurrences and accommodations that are made both to the innovative technology (in this case BIPV) and to its complex local physical (in this case the building) and processual (in this case the project management processes) context during its adoption. This aim is supported by three objectives:

- To explore how the building and the technology develop as design decisions are made during the project when BIPV is incorporated;
- To examine what may influence the installed generation potential of the buildings;
- To explore the implications of this research for the adoption of BIPV and other sustainable technologies.

The analysis documented the mutual constitution of the technology and the building for each project and then compared the case studies to explore themes of integration and co-development across the projects. These themes were used to move from an analysis of the three specific cases to a re-engagement with the literature on the adoption of technology. The discussion explored how BIPV challenged a number of basic assumptions which inform research into innovation and construction management literatures. The discussion chapter highlighted how innovation occurs on-site as construction of the building proceeds and explores the implication of this in the adoption of integrated technologies.

Rather than using formal roles (architect, designer, project manager etc.) and project stages (initial design, tender, detail design etc.) to explain adoption, the research found that the actors formed informal groups around particular interests and that the make-up of these groups shifted and changed with rhythms that sometimes followed the standard project stages, but sometimes followed a different logic. Decision-making was dominated by a particular frame at different times, and it was not always the seemingly obvious frames which dominated decision-making and shaped the technology. Decisions which took into account the characteristics of the BIPV and the building stemmed from the ability of actors to mobilise multiple frames when problem solving and often resulted in innovation.

This research design viewed adoption as a process, rather than a moment and explored the dynamic nature of that process by examining the co-development of the BIPV system and the building as the projects progressed. The micro-level socio-technical analysis showed that innovation and product development of both the BIPV system and the building continued well into construction and adoption. The approach used has given a more detailed understanding of the complexity of the adoption of innovation in construction projects and points to several threads for future research into the adoption of integrated technologies.

This chapter summarises the key theoretical contributions of this research before moving to specific conclusions for each of the research objectives. It goes on to identify the methodological contributions and then summarises practical implications for policy makers and practitioners. Finally, the limits of the research and future areas of research are highlighted.

11.1 Theoretical contributions

This section looks at the theoretical contributions of this research to both construction and innovation theory, and to the SCOT approach.

11.1.1 **Construction management and innovation theory**

The notable absence of literature surrounding the adoption of technology in buildings and the failure of integrated renewable technologies to deliver their promised performance suggests that additional research is needed in this area. The case of BIPV directly challenges a number of basic assumptions which inform research into innovation in general and sustainable innovation in particular. In much of the literature, innovation, product development, commercialisation and adoption are treated as distinct stages in a linear process (e.g. Rothwell, 1994). Alternatively innovation is treated largely as a process which must be managed (Poole et al., 2000; Pettigrew, 2012). Although both these social and technical aspects of an innovative technology influence adoption (Lees & Sexton, 2013), they are often treated as radically distinct, with researchers focusing on one or the other. Finally, technology as products are depicted as uniform, standardized, stable physical artefacts with a clear manufacturer and expert knowledge (Yang, 2015; Kissi et al., 2012).

Chapter three pointed to two important omissions in literature. Firstly, there is little micro-level empirical study which combines both the technological and social elements which occur as innovation is incorporated into building or projects (notable exceptions include Harty (2008) and Tryggestad & Georg (2011)). Second, the impact that the process of adoption has on the generation potential of the BIPV system is neglected in favour of technical developments (Sozer & Elnimeiri, 2007; Laird, 2010) and the importance of policy and certification (Pagliaro et al., 2010; BRE, 2015). In addition, much literature on implementing innovation in construction focusses on strengthening project management procedures (Love and Li, 2000; Sun and Meng, 2009; Bourne, 2001; Cooke-Davis, 2002), integrating the supply chain (Bresnen & Marshall, 2000; Briscoe et al., 2001) and improving decision making (Krishnan et al. 2001; Chinowsky et al., 2008; Bakht & El-Diraby, 2015). This attention to the optimisation of construction processes fails to recognise the bespoke nature of integrated technologies and the corresponding challenges for their incorporation into buildings. It also fails to show how different decision modes directly affect both the performance of the technology and subsequent chains of decisions making.

The application of a socio-technical approach and the empirical findings allow comment on the incorporation of innovative technology at the project level. In contrast to approaches which seek to model innovation adoption (Slaughter, 1998; Tidd, 2006), prescribe best practice (Cooke-Davis, 2002) or instruct managers in the management of innovation (Van de Ven et al., 1989) this research has led to a more nuanced, processual understanding of adoption. The consideration of decision making arising from the resolution of problems which arose as the technology was incorporated into buildings and the understanding of the sociological and technical requirements of the actors in projects teams suggest that there are a number of issues in addition to technical or economic considerations which influence the adoption of technology and affect its performance.

One significant area of contribution is to the study of construction project management from the “soft skills approach” which recognises the importance of skills needed to manage projects (Crawford et al., 2006; Dainty et al., 2003; Olson et al., 2001) and to literature which moves from problem solving to problem structuring (Franco et al., 2004). This research into the micro-level adaptations which occur as BIPV is incorporated into a building project supports the notion that different project actors bring different perspectives to problem solving (problem structuring) (Franco et al., 2004) and makes a new contribution in highlighting the way that these perspectives shift during the project. In addition, although conventionally people with the same job title have been assumed to share the same views and prioritise certain issues, this research suggests that this is not the case and that the perspective of project actors shifts throughout the project and that this shift is not solely related to the project stage.

The findings within this research also comment on studies which focus particularly on the processual view of innovation (Van de Ven et al., 1989) and the interconnections which flow across projects and between project actors (Harty, 2008b; Schweber & Harty, 2010). The Social Construction of Technology approach (SCOT) (Bijker, 2009) allowed analysis of actors' interests and their changing relationship with the artefacts which provided a way to explore the co-development of the technology and the building, and the adoption process.

11.1.2 **Contribution to the SCOT approach**

Within the SCOT approach identification of relevant social groups, technological frames and the development of a network of problems and solutions are well known and often cited (Aibar & Bijker, 1997; Walter & Styhre, 2013; Howcroft & Light, 2010). However the final stage of the social construction of technology approach is the development of mechanisms of stabilisation and closure which is recognised by Bijker et al.(2012) as being somewhat under developed. The loosely defined SCOT approach has few detailed empirical examples of how to conduct a SCOT analysis and this case study analysis adds to that limited store by providing a step-by-step approach to operationalise SCOT. In addition this research makes a contribution to the mechanisms of stabilisation and closure by bringing the dynamics of adoption into focus and allowing an understanding of how decisions are made and the effects of those decisions on BIPV, the building artefacts and the actors.

The SCOT approach generally takes into account the development of material technology (Bijker, 2009), but in this research it became clear that some social artefacts such as schedules and contracts had an equal role in the stabilisation and closure of the technological system. The focus of the research on the mutual constitution of the BIPV system and the building allowed for consideration of the impact of the local context on the adoption of technology, rather than considering the technology as an isolated artefact. Using SCOT to operationalise social artefacts was not straight-forward and is an area where SCOT was less able to provide an understanding of the dynamics of decision-making.

The technological frame is one of the key analytical constructs of the SCOT approach and has been used in this research in line with Bijker's outline (Bijker, 1999). During the analysis of the case studies it became clear that the technological frame remains a somewhat ambiguous concept particularly in relationship to social artefacts such as contracts and risk. Technological frames were introduced by Bijker et al in response to concerns about semiotic theories of power (Bijker et al. 2012; Klein & Kleinman, 2002), but from the case studies it seems that artefacts can be invested with power which is not necessarily obvious to the actors. This makes analysis of the decision-making motivations and processes in the design process more complex than the SCOT approach and much construction management literature would suggest.

A classic use of the SCOT approach is to explore how an artefact arrived at technical stabilisation over a period of time (Aibar & Bijker, 1997; Bijker, 2009). In a similar way to the comparison methods used in process innovation approach, the case study comparison has highlighted similar patterns in the adoption process across the three case studies. The case study comparison of this research has provided a template for the front-end design of a construction project which is an addition to the standard problematic addressed by SCOT research.

11.2 Summary of key conclusions to the research aim and objectives

The case studies have shown that process of adoption of BIPV cannot be contained within a single model and is far more complex than a single stage in an innovation model would suggest. The prevailing view of adoption of technology within construction management literature does not take into account the conflicting interests of project actors and the shifting focus of decision taking. In the cases studied, these conflicts and shifting foci resulted in unexpected mutual articulation of the buildings and technology which in two cases has had detrimental effects on the generation potential of the BIPV systems. These findings translate to other integrated renewable technologies which are increasingly specified on building projects. .

11.2.1 **The mutual articulation of a building and the technology.**

The research showed three types of co-development mechanisms - lock in, homogeneity of appearance, and mutual adjustment and adaptation. Each of these mechanisms resulted from different ways of making decisions and gave rise to particular characteristics of co-development and subsequent performance of the technology.

Decision-making during the case studies depended on how the project actors understood the challenges of adoption. Integrated decision-making occurred when actors had the flexibility and awareness to mobilise multiple technological frames and often resulted in the development of innovative solutions which simplified adoption. On the other hand, actors making limited use of technological frames used discrete decisions making, without reference to the effects of the decisions on either the BIPV system itself or on the building, and these decisions resulted in a rather disjointed and ad-hoc adoption process which compromised the generation potential of the technology. At times the dominant logic for decision making came from a source which was not obvious which then disappeared, making the logic hard to follow (for example when decisions were taken that seemed to follow from an unwillingness to engage with the technology but were actually based on a desire to minimise risk).

The friction interfaces or points of friction - where the BIPV assemblage and building physically connected with part of the building - were not apparent to the project teams from the outset of the project, but were stumbled upon at unexpected points as the projects proceeded. This resulted in unplanned mutual articulation of the technology and building and affected the performance of the technology and appearance of the building

Analysis of the co-development of the building (with all its component technologies and parts) and the BIPV system drew attention to the role of social artefacts in the processes of adoption. Contracts, schedules and risk were often un-articulated reasons for decision making which obscured technological implications and prevented integrated development of the building and technology. Conclusions about the practical implications for parts of the standard construction project procurement process on the adoption of integrated technologies are detailed in section 11.4 – Implications for practice and practitioners.

11.2.2 **Influences on the delivered generation potential of the buildings**

The bespoke character of BIPV would suggest that the BIPV system and the building would be designed together. However, the data did not support this and pointed to an independence of design which often came together only at the point at which the technology was integrated within the building (integration interfaces). This demonstrated that the integrated characteristics of the BIPV technology were often obscured, as the technology was treated as a series of components which had to be accommodated within the building

Project actors used different criteria to assess the technology and to make decisions at different times of the project. The issue that this raises is how to keep visible the criteria associated with the innovation’s performance, rather than the more obvious goals of project delivery and cost. The surprising absence of a group being concerned with generation maximisation shows that it is not always the seemingly obvious groups which dominate decision-making and shape the technology.

Innovation adoption relied on multiple actors informally taking up the role of systems integrator at different times. The systems integrator is a shifting, informal role within a project team and as the person fulfilling the task of systems integrator changed through the projects, so did the perceived locus of expertise. In this way responsibility for system design moved through the project team without anyone actually formally assuming responsibility, so that by the end of two of the case studies the BIPV systems had been implemented without ever having been designed. This empirical evidence contradicts much construction management and project management literature which puts great store on the stage-wise management of projects and concepts such as the “design freeze” (Cooke-Davis, 2002; Winch, 2010).

Instead of adding clarity and focus to the adoption process, the effect of policy and certification was mixed and in two of the cases resulted in fragmented adoption, with BIPV systems not making any significant contribution to electricity production. The process of adoption was complicated by confusing generation targets, ill-thought out commissioning procedures, and lack of attention to measuring generation output.

11.2.3 The implications of this research for the adoption of BIPV and other integrated technologies

The bespoke systems character of BIPV and the local context into which it is incorporated means that innovation and product development continue well into commercialisation and adoption. The plethora of options for component choice and configuration of integrated technologies is both a blessing and a curse: it allows unique solutions to be developed for each application; but also means that there is no single accepted convention in terms of component selection, matching and configuration. In terms of adoption, this lack of standardisation creates problems of understanding and communication across the project team and is likely to be repeated for other integrated technologies. The technical complexity of the integrated technologies means that clients and developers tend to focus on the visible features of the technical system, innovation continues well into adoption, and its incorporation spreads across multiple work packages - often at the expense of standard contractual structures and procedures.

As with BIPV, the inclusion of other integrated technologies in construction projects will pose challenges. These included: the failure to appreciate the integrated nature of the technology; the tendency of the building project team to privilege visible aspects of the BIPV system over the electrical system; and the implications of initial design decisions for the incorporation and generation potential of the technology. The analysis has highlighted the way in which failure to anticipate and plan for the effect of particular decisions on other aspects of the interdependent systems posed problems for the team and potentially compromised initial technical and design goals.

Considerable innovation and development occurs on site as construction of the building unfolds. With integrated technologies there is no single product and there is no single expert. Instead, expertise resides in diffuse pools of different types of knowledge and these silos rarely come together in cohesive product development or design efforts.

11.3 Contributions of the method to the analysis

The use of SCOT to analyse the incorporation of BIPV on three construction projects has made contributions to construction management literature and contributions towards the development of the method (section 11.1).

The Social Construction of Technology approach (SCOT) was used to analyse the process of incorporating the technology as a series of problems and solutions which unfolded as different actors' interests were involved with different artefacts of the technology and building. Eight technological frames were found to account for the actors' interests: Generation Maximiser; Green Guardian; Design Aesthete; Design Optimiser; User, Cost Watcher; Time Sentry; and Risk Minimiser. The artefacts under consideration included the individual components of the BIPV system (panels, inverters wiring etc.) and the parts of the building with which the technology interfaces (façade, roof, electrical systems etc.). Issues which were examined included the changing interests of the actors, the network of problems and possible solutions and the effects of the chosen solution on the rest of the project. The SCOT analysis of actors' interests and their changing relationship with the artefacts provided a way to explore the co-development of the technology and the building, and the adoption process.

The SCOT approach showed that within a project team, groups of actors coalesce around interests which transcend simple job title. Membership of these groups within the projects shifted and changed with rhythms that sometimes followed the standard project stages (initial design, tender, detail design etc.) but sometimes followed a different pattern. This understanding contributes to construction management literature by offering a new perspective how the interests of stakeholders within a construction project evolve over the course of a project.

The SCOT approach allowed the standard boundaries of project processes to be deconstructed and allowed the researcher to follow threads of problems and solutions across the whole project. As a contribution to construction management literature on innovation, this gave a clear view of how the technology and building developed and how this development is influenced by the contractual nature of construction projects.

11.4 Implications for practitioners and practice

Analysis of the case studies highlighted several practical implications for construction professionals. These implications broadly fall under two banners: project procurement processes; and challenges associated with the adoption of innovative integrated technologies.

Project procurement covers all aspects of the delivery of a project from concept to handover and sometimes beyond. The analysis has shown that current procedures and processes do not always support innovation adoption and indeed that they can hold back adoption. Findings from this research conflict with those who argue that more efficient and rigorous implementation of project procedures (Cooke-Davis, 2002) and further integration of the supply chain assist adoption of innovation (Egan, 1998; Wolstenholme, 2009). In particular the development of work packages prior to tender can divide the BIPV system into separate mechanical and electrical contracts and this de-coupling makes integrated system design difficult. This practice has major implications for many other technologies and the points of integration need to be carefully considered.

Whilst measuring the delivered output from BIPV is complicated, it is often just as difficult to determine the theoretical output of the design and this shows that commissioning of BIPV systems needs integrated consideration, and suggests that commissioning procedures and contracts should take this into account.

Several key challenges associated with the adoption of integrated technologies in construction projects were identified such as: identification of points of friction (friction interfaces); definition of work packages; and maintaining the purpose of the technology throughout the process of adoption. These challenges also apply to the adoption of other more established systems (such as ground source heat pumps, district heating, chilled beams etc.) but are generally less visible because ways of working have been adapted to accommodate them.

Analysis of the three case studies showed that there is no single accepted way of selecting components, matching their outputs and configuring the system. The lack of guidance in system design makes efficient design and consistency of approach challenging and an efficient outcome unlikely. A suggestion would be that practitioners should focus on understanding how to use the technology as a system rather than focussing on individual components.

Findings show that BIPV expertise resides in diffuse pools of different types of knowledge and that this knowledge and expertise rarely comes together in cohesive product development or design. Project managers should consider carefully where the expertise resides, rather than making assumptions about the technology. The research indicates that the informal role of systems integrator plays a key part in the design and installation of the system. The system integrator role can reside with multiple actors though a project but this shifting locus of perceived expertise can be a false friend to the project team, giving the impression that someone is designing the system as a whole, whilst in reality it is just evolving on an ad-hoc basis.

This research draws attention to the limitations that standard project procurement processes place on the adoption of technology. Particular ways of working brought about by project management practices and contract management did not support the adoption of BIPV and in particular conventional mechanical and electrical demarcations created artificial barriers between parts of the technological system. In addition, changing project personnel as a result of standard Design and Build practices meant that the rationale or history behind decisions was lost and knowledge was siloed amongst project team members..

11.5 Implications for Policy

This research contradicts authors who believe that Feed-in-Tariff and other financial incentives would increase adoption of green technologies by driving the delivery of efficient systems to maximise income from the electricity generated (Lowe, 2007; Yang & Zou, 2015). In the case studies not one of the actors on any case study mentioned Feed-in-Tariffs at all.

Attention is drawn in this research to the negative effect that BREEAM certification and Energy Performance Certificates for buildings had on the specification of the BIPV systems. The effect of the certifications was to introduce a “tick box” mentality which failed to focus attention on generation targets. Only when specific generation targets were stipulated as planning requirements did the output of the BIPV system become important. This conclusion supports assertions by Schweber (2013) and Russell and Thompson (2009) that the effect of policy is not always in line with the desired policy outcome.

In research little attention has been paid to the initial lack of target generation figures on projects and to the difficulty of measuring the achieved output. While targets specified on paper versus those achieved in practice are often difficult to measure, check or validate (Gorse et al., 2012), the case studies showed that adoption of BIPV was additionally complicated by confusing generation targets, ill-thought out commissioning procedures, and varying weather conditions over the period of commissioning. The result of a lack of focus of policy on holding design teams to account for meeting predicted outputs is clearly indicated by this research.

11.6 Implications for design

Analysis of the case studies has shown that there is an additional dimension to be considered in terms of the performance of the assemblage of the innovation, rather than just its impact in the project process. It is interesting to reflect that there is very little literature which focusses on designing efficient, integrated BIPV systems, and that the current focus on improving individual components can only go part of the way to facilitating adoption.

Early division of design work between mechanical and electrical disciplines, and the very early development of work packages before detail BIPV system design had taken place, made it difficult to integrate all the elements of the BIPV system and for an assessment of the whole BIPV system performance to take place. Similarly, the process of tender and awarding of contracts relied on previous relationships and understanding affected the ability of the contractor to deliver the work package. These findings point towards a need to re-cast the specialist trades or specialist engineering relationships within the pre-tender/tender stages of standard management of construction projects. The SCOT approach did not allow for these findings to be unpacked fully and this would indicate a direction for future researchers to embrace.

One additional implication for design is the unwillingness of suppliers to engage heavily in projects before contracts are signed. This reluctance springs from the fear that they will give away their specialised knowledge without gaining the contract. It appeared that the standard project processes discouraged suppliers from putting detailed design of the BIPV system into the early stages of the project because of the uncertainty of winning tenders and potentially giving information to competitors. This reluctance represents a two-way loss: the project design and management teams loose valuable expertise in developing thorough front-end design; and the specialist supplier loses an opportunity to influence the design to best showcase the technology.

11.7 Limits of the research and suggestions for further research

11.7.1 **Limitations**

This research has provided a rich source of data for understanding the dynamic nature of adoption and of exploring how integrated technology is incorporated into buildings. The SCOT approach allowed for a detailed analysis of problem solving and decision-making throughout the process of adoption and showed how the technology and building evolve as the project continues.

Limitations of this research centre on the limited way that the SCOT approach can be used to theorise the link between processes of stabilisation and mechanisms of closure. This research contributes to the operationalisation of the concepts of stabilisation processes and closure mechanisms by identifying particular decision-making modes and types of co-development which occurred over the course of the case studies. However the relationship between these two concepts remains elusive and so although this research can point to different decision making modes, it could not develop the connection further. A further major limitation of this research is the analysis of the decision-making motivations and processes in the design phases of the case studies. The concept of the technological frame remains somewhat ambiguous with respect to issues of semiotic power – particularly with respect to the social artefacts of contracts and risk – the decision-making motivations and processes were shown to be more complex than the SCOT approach would suggest. Further research using a different epistemological approach would be needed to refine the findings of this research in terms of decision-making modes, stabilisation and closure in order to make an even more significant contribution to construction project management literatures.

A detailed analysis of social artefacts, project processes and procedures which impact adoption of new technology fell outside the scope of the research and some of these possible avenues of further work are suggested below.

11.7.2 **Suggestions for further research**

The analysis and findings from this research suggest a number of possible directions for future research investigations. These are presented in order of importance and achievability.

The occurrence and effect of integrated decision-making and discrete decision-making on the adoption of technology could be further explored, particularly with regard to understanding how stabilisation and closure mechanisms develop. This could be achieved by conducting a more detailed, longitudinal study of a single project, with on-site attendance.

The effect of project procedures and practices on the adoption of integrated innovations would also be an interesting line of research, building on the finding of this research that standard ways of working hindered adoption of BIPV. This could be conducted by exploring project processes in more depth and examining how they constrain or promote adoption within the project team. A comparative case study might give useful insights into how these standard procedures could be changed to enable adoption.

Further exploration of the role of social artefacts (such as contracts and schedules) in co-development is a third possible direction for research. Findings from this research suggest that social artefacts have a disproportionately large effect on co-development, but equally found the SCOT approach to have limits in developing this theme. A new approach to exploring this phenomenon should be explored.

One of the key analytical constructs of the SCOT approach – the technological frame – is somewhat ambiguous in terms of its relationship to the social artefacts and notions of power. A more comprehensive understanding of this concept could be developed further by considering these relationships.

A final avenue of future research would be to expand this socio technical analysis to other green technologies so as to allow the debate on the adoption of sustainable innovations to move forward. It is only once a more dynamic model of innovation adoption is developed that a fuller understanding of the nature of integrated sustainable innovation can be developed.

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Appendices

A1: Pilot Interview Schedule

Diffusion of Sustainable Technology – accommodations to building design and practices in the adoption of low carbon technologies

Interview Schedule: Initial Round A

Date of Interview: 10/12/13 Name ID: LE01A

Introduce myself and the research

How I got here, my story

How the research came about, what interests me

This is what it's about

Background

How came to be involved in the firm/product?

How firm came to be manufacturing product/using the product?

Competitors?

Issues

What kinds of issues have come about during adoption?

What kind of feedback has he had from adoption?

Ask about projects which come to mind

What might be interesting about them?

Why those ones?

Different actors, client, confidentiality?

Access: who needs to give consent – gate keepers?

A2: Case Study Interview Schedule

Diffusion of Sustainable Technology – accommodations to building design and practices in the adoption of low carbon technologies

Interview Schedule: Case Study OS

Date of Interview: 03/06/2015 Name ID: OSFW03B

Introduce myself and the research

Background

Tell me about self – how came to be doing this, firms, type of projects

How/when came to be involved in the project

How firm came to be doing project

Do you have any personal engagement with sustainability?

Project

Tell me about the project

Role on the project

Other people involved in the project – internal/external to firm – their engagement with sustainability?

Had any members of the project team worked together before?

Issues

What were the challenges/issues in general?

Did technology pose any challenges/issues?

What parts? Who was involved in the solution? What was their role? Why were they involved?

Did that have any knock-on effects?

Did parts of the design change as a result of technology used?

Did using the technology affect/change the way that you worked?

What would other people who worked on the project say about the technology?

Particular

How did the design evolve? What were the key points/decisions, who took them?

What was the process of arriving at the curved roof? What options were considered?

How were micro invertors arrived at – who was involved in the discussion?

(Sub-collectors, wiring routes, BMU, maintenance, replacement, Risk, Experience, Commissioning)

A3: Technological Frames

	Green Guardian	**Cost Watcher**	**Generation Maximiser**
Goals	- Buildings should generate energy - Reduction of carbon emissions	- Building comes in on budget - Profit margins maximised - Extras are minimised	- The PV system is as efficient as possible - Losses are minimised - Generation is maximised
Problems	- Green solutions are often "casualties of war" - Green solutions generally cost more	- Renewable solutions are costly - Innovations often lead to extra costs	- Weather changes - There are many models - There are different technologies and layouts available and there is an optimal one - Authority
Strategies	- Enshrine in planning regs	- Make work packages as comprehensive as possible - Control extras - Minimise innovation	- Use new technologies/advances - Take time to set things out - Reduce wiring runs
Tacit Knowledge	- Technology available - Planning requirements	- What everything costs - Re-jigging packages reduce cost	- Technology available - Electricity and electronics -
Testing procedures	- Output figures - m2 of PV	- Review meetings	- Flash tests - Simulations
Design Methods	- BREEAM	- Work packages	- Simulation programmes calculate and optimise output
Criteria	- Merton, KWh	- Final project cost	- kWh meets target

A3: Technological Frames (continued)

	Design Aesthete	**Design Optimiser**	**User**
Goals	- The PV adds an aesthetic element to the build - There is a degree of novelty to the build	- Build-ability of the project - The building and PV are designed to fit together	- System can be monitored - Electricity is generated - System can be maintained - Looks good and is pleasant to work in
Problems	- New technologies bring unknowns - Wiring needs to go from outside to inside - Outline schemes not detailed - Experts are wary of detailed involvement - Keeping up to date with possibilities - No “go to“ expert for the system - Knowing what is a show stopper	- Work parcels make artificial demarcations - Details of the interfaces between the parts are “dropped” - There is no time to make the design “perfect”	- Represented after the event - Not part of the initial design team - Get what they get
Strategies	- Rely on experts - Try to make specs so specific that the favoured supplier gets the contract - Try to get tied in to the project early	- Develop “on the hoof” strategies - Plan before you start - Understand system needs - Check overlap of work packages	- Rely on contractor for representation - “Snagging” on handover
Tacit Knowledge	- Aesthetic contribution - Finishes available - Standards of finish	- Past experience	- How it will be used

Testing procedures	- Durability	- Good design practice	- BMS
Design Methods	-	-	-
Criteria	- Looks good	- No Extras	- Get what paid for

A3a: Additional technological Frames developed during analysis

	Time Sentry	**Risk Minimiser**
Goals	- Project is delivered on time - Delays are minimised	- Minimise risk of contravening contract - Minimise risk of failure
Problems	- Schedule is drawn up before tender packages are agreed - Design changes cause delays	- New technology poses risk to the integrity of the usual, known design - Departures from the norm may affect ability to deliver on time - New designs may have unanticipated knock-on effects
Strategies	- Understand work packages - Planning meetings	- Do not take on anything new - Ensure that work packages do not include unknowns - Do lots of research
Tacit Knowledge	- Past experience	- Contracts, Warranties,
Testing procedures	- Will it affect schedule?	- Will I be liable?
Design Methods	- Scheduling packages	- Contract
Criteria	- Completed to time	- No claims

A4: Coding Node Structure Report

Node

Nodes

Hierarchical Name	Nickname	Aggregate	User Assigned Color
Nodes\\Artefact		No	None
Nodes\\Artefact\Cells		No	None
Nodes\\Artefact\cleaning		No	None
Nodes\\Artefact\façade		No	None
Nodes\\Artefact\inverter		No	None
Nodes\\Artefact\wiring		No	None
Nodes\\Background		No	None
Nodes\\Background\Company Background		No	None
Nodes\\Background\Interviewee Background		No	None
Nodes\\Characteristics of BIPV		No	None
Nodes\\choice of technology		No	None
Nodes\\Contract		No	None
Nodes\\Contract\Stage at shich individual involved		No	None
Nodes\\Contract\Stage at which problem identified		No	None
Nodes\\Contract\Type		No	None
Nodes\\Design evolution		No	None
Nodes\\Familiarity with technology		No	None
Nodes\\Familiarity with technology\Firm		No	None
Nodes\\Familiarity with technology\Individual		No	None
Nodes\\Familiarity with technology\Previous involvment with PV		No	None
Nodes\\Frame		No	None
Nodes\\Frame\Degree of inclusion		No	None
Nodes\\Frame\goals, ideas and tools		No	None
Nodes\\Frame\Meaning		No	None
Nodes\\Impact		No	None
Nodes\\Impact\Design of building		No	None
Nodes\\Impact\Design of PV		No	None
Nodes\\Impact\on Project		No	None
Nodes\\Interfaces		No	None
Nodes\\Interfaces\With building		No	None

Nodes\\Interfaces\With other parts of PV system	No	None
Nodes\\Planning	No	None
Nodes\\Problems, solutions and negotiations	No	None
Nodes\\Problems, solutions and negotiations\Access	No	None
Nodes\\Problems, solutions and negotiations\arising from building design	No	None
Nodes\\Problems, solutions and negotiations\Arising from process or individual	No	None
Nodes\\Problems, solutions and negotiations\cells	No	None
Nodes\\Problems, solutions and negotiations\contract	No	None
Nodes\\Problems, solutions and negotiations\cost	No	None
Nodes\\Problems, solutions and negotiations\Façade	No	None
Nodes\\Problems, solutions and negotiations\Finding contractors or suppliers	No	None
Nodes\\Problems, solutions and negotiations\generation potential	No	None
Nodes\\Problems, solutions and negotiations\invertor	No	None
Nodes\\Problems, solutions and negotiations\maintenance	No	None
Nodes\\Problems, solutions and negotiations\PV design	No	None
Nodes\\Problems, solutions and negotiations\Schedule	No	None
Nodes\\Problems, solutions and negotiations\Selection of PV	No	None
Nodes\\Problems, solutions and negotiations\wiring	No	None
Nodes\\Project Details	No	None
Nodes\\Project Details\Firm involvement in project	No	None
Nodes\\Project Details\Interviewee involvement in project	No	None
Nodes\\Project Details\Project description	No	None
Nodes\\Project Details\Project history	No	None
Nodes\\Project Meanings or rationale	No	None
Nodes\\Project Meanings or rationale\BREEAM	No	None
Nodes\\Project Meanings or rationale\Reasons for building	No	None
Nodes\\Project Meanings or rationale\reasons for pv	No	None
Nodes\\project role	No	None
Nodes\\Risk	No	None
Nodes\\RSG	No	None
Nodes\\RSG\Cost Watcher	No	None
Nodes\\RSG\Design Aesthete	No	None
Nodes\\RSG\Design Optimisers	No	None
Nodes\\RSG\Generation Maximiser	No	None
Nodes\\RSG\Green Guardian	No	None
Nodes\\RSG\Users	No	None
Nodes\\Tension	No	None

A5: Sample project information form and consent form

Information Sheet

Pippa Boyd

School of Construction Management and Engineering,

Room 2N16, URS Building,

The University of Reading, PO Box 225,

Reading,

RG6 6AY.

Diffusion of Sustainable Technology – accommodations to design and practices in the adoption of low carbon technologies

My name is Pippa Boyd and I am a PhD researcher in the School of Construction Management and Engineering at the University of Reading.

I am carrying out a research project to investigate how the specification of a new technology within a building project potentially introduces new challenges and problems for the project teams. I am particularly interested in understanding how the incorporation of a new low carbon technology on a build may impact ways of working by the project team - both in terms of the way that the building develops and the accommodations made to ways of working by the team members. I am interested in the changes made to the building design as a result of the new technology and changes to practices of various project team members within the project as it develops (such as the supplier, design consultants, construction personnel and commissioning organisation).

With your consent I would like to record the meeting and transcribe sections later for analysis. Your participation within the research is entirely voluntary. I can turn off the tape recorder at any time during the meeting / discussions. Copies of the transcript will be available on request and any changes which you request will be made. The data will be kept securely and destroyed when the research has ended. The data will be used for academic purposes only. You are free to withdraw from the study at any time; if this is the case the information and discussions given by you during the meetings will not be used during the analysis of the data.

At every stage, your identity will remain confidential. Your name and all identifying information will be removed from the written transcript. My supervisors Dr Graeme Larsen and Dr Libby Schweber, and I will be the only people who will have access to this data.

Copies of the completed reports will be available on request. If you have any further questions about the study, please feel free to contact me at the above address.

This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee, and has been approved.

Diffusion of Sustainable Technology – accommodations to design and practices in the adoption of low carbon technologies

Consent Form

1. I have read and had explained to me by Pippa Boyd the Information Sheet relating to this project and any questions have been answered to my satisfaction.

2. I understand that my participation is entirely voluntary and that I have the right to withdraw from the project at any time, and that this will be without detriment.

3. I understand that my personal information will remain confidential to the researcher at the University of Reading, unless my explicit consent is given.

4. I understand that my organisation will not be identified either directly or indirectly without my consent.

5. I agree to the arrangements described in the Information Sheet in so far as they relate to my participation.

6. Would you like to review the transcript before used? Y / N
(please circle)

Signed	
Print Name	
Date	