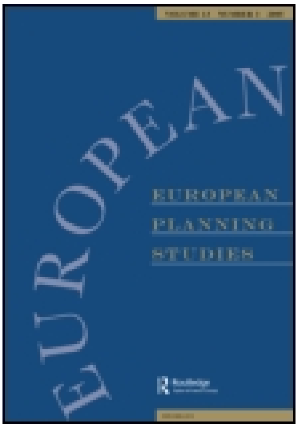

European Planning Studies
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ceps20

Improving Energy Efficiency of Social Housing Areas: A Case Study of a Retrofit Achieving an "A" Energy Performance Rating in the UK

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Available online: 24 Jan 2012

European Planning Studies Vol. 20, No. 1, January 2012

Routledge
Taylor & Francis Group

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(Received 26 January 2011; accepted 1 February 2011)

ABSTRACT *Currently, the majority of the European housing stock falls towards the bottom of the energy efficiency rating scale on the EU Energy Performance Certificate. If governments and businesses are to successfully address ambitious CO_2 reduction targets, then it will be imperative that energy-efficient measures and policies focus on existing housing. In order to understand what kind of retrofit is needed to achieve an "A" energy performance rating in social housing, the paper reports the findings of an on-going research project in the UK. The paper draws on a case study from the Technology Strategy Board's "Retrofit for the Future" competition entry in Cambridge. The upgrade strategy improved the home's energy performance rating to A, aimed to radically reduce carbon dioxide emissions (17 kg m^{-2} $year^{-1}$) and provided affordable warmth for the tenants. In order to get an impression of the actual energy consumption in the case study, energy use behaviour of the household was observed. Based on the barriers identified in the case study, the feasibility of the current UK policy strategies (e.g. Smart Meters and Feed-in-Tariffs) to facilitate the acceptance of energy measures in social housing is discussed.*

1. Introduction

The UK government strategy "Warm homes, greener homes" aims to cut household carbon emissions by 29% by 2020. By 2015, every household should have loft and cavity wall insulation, and by 2020, up to 7 million homes should have more substantial improvements such as solid wall insulation or renewable energy technologies (HM Government, 2010). If governments and businesses are to successfully address ambitious

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ISSN 0965-4313 Print/ISSN 1469-5944 Online/12/010131–15
http://dx.doi.org/10.1080/09654313.2011.638494

CO_2 reduction targets, then it will be imperative that planning and energy policies address the existing housing stock (Boardman *et al.*, 2005; Sunikka, 2006; Meijer *et al.*, 2009).

Understanding how an energy-efficient retrofit works in practice is vital in lowering the overall household energy consumption. This paper investigates how an "A" energy performance rating can be reached in a retrofit, considering energy efficiency measures, the use of solar energy and the characteristics of household energy use behaviour. The paper is not limited to energy simulations, but draws on real data from the winning entry to the "Retrofit for the Future", an on-going project funded by Technology Strategy Board (TSB) in 2009/2010. The team consisted of PRP Architects, Hill Partnerships and the Cambridge City Council and Cambridge University. The paper aims to answer the following research questions.

1. How is the level "A" energy rating performance achieved in a social housing retrofit in the UK case study?
2. What are the characteristics of household energy use in the retrofit case study?
3. How do policy instruments such as Smart Meters and Feed-in-Tariffs (FIT) facilitate energy savings in the social housing sector in the UK?

Section 2 presents the methodology. Technical measures and the retrofit process are described in Section 3. Section 4 discusses the characteristics of the household's energy use behaviour in the case study. Section 5 focuses on the current UK policy strategies and their effectiveness in social housing. Conclusions are drawn in Section 6.

2. Methodology

Due to the diversity of the housing stock, barriers to energy saving differ per tenure (Sunikka, 2006; Meijer *et al.*, 2009). This research focuses on social housing where economic constraints are dominant, but the stock managed by professional landlords making the decision-making process easier than in the private rental sector. The UK social housing sector provides affordable housing for households with an average income of less than £11,000 a year. In total, a 29% reduction in the emissions from 2008 levels is expected from the UK social housing sector by 2020 (Communities and Local Government, 2010). Saving targets are driven by the fact that around 20% of houses in major regions in the UK is estimated to suffer from energy poverty (Pollitt, 2010). The new "Warm Home" standard aims to raise the energy efficiency standard of social housing from around Standard Assessment Procedure (SAP) 59 to at least 70 (HM Government, 2010)—if the new coalition government will follow the policy. The SAP is adopted by Government as the UK methodology for calculating the energy performance and CO_2 emissions of dwellings (BRE, 2009). Based on the floor area, volume, infiltration, opening areas and U-value of different elements, the SAP calculates the heat losses, internal gains, lighting and water heating demand. This information is turned into an energy consumption figure, considering the information provided about the ventilation, space and water heating systems. Building orientation and obstructions to sunlight are used to calculate solar gains and contribution of micro-renewables. Any considerations about building occupancy and use are in proportion to the dwelling area and cannot be changed. In order to overcome financial barriers, a "Green Deal" approach will be introduced to financing upgrades; energy companies will be obliged to support householders in energy saving, including subsidies and free upgrades for households identified as vulnerable (HM Government, 2010).

The case study is located in a social housing area at the southwest side of Cambridge city, in Trumpington. The social housing scheme, which today is partly owned by the Cambridge City Council, was built in the 1950s by the British Steel Homes company as part of the large housing development. The case study (Section 3) and most houses in the area (participating in the survey in Section 4) are all identical three-bed semi-detached properties (86 m^2 floor area), constructed using a steel frame (BISF) structure. Most of the households receive housing benefits, are considered as "fuel-poor" (paying more than 10% of their household income for energy) and, due to their economic situation, are pre-pay metre (PPM) clients, with high energy tariffs than in a traditional contract. As a part of the TSB "Retrofit for the Future" competition, the case study was retrofitted and monitored as a prototype for other social housing in the area.

The retrofit strategy had to be feasible and replicable on a mass scale to any house of this type in any location in the UK. In total, 36,000 BISF houses and 1500 steel-framed Howard Houses were built after the war in the UK. A more ambitious Passivhaus standard, where the heating demand would be reduced to $<$15 kWh m^{-2} $year^{-1}$, would have required mechanical ventilation, heat recovery and higher insulation levels in the case study—especially in walls and floor—and the elimination of all cold bridges. Despite the mechanical ventilation, there were doubts whether a tight Passivhaus envelope was suitable as the couple smoke indoors and have pets. Furthermore, according to Galvin (2010), the higher the thermal renovation standard, the higher the cost in terms of money invested per unit of energy saved; the Passivhaus standard being less cost-effective compared with a normal retrofit that complies with the building regulations.

Occupant behaviour and household characteristics have emerged as important contributors to domestic energy consumption (Liao & Chang, 2002). Heating energy saving achieved through retrofit measures can be remarkably lower than calculated (Haas & Biermayr, 2000). There seems to be up to 50% difference in energy consumption between the prediction and the reality in a retrofit—and very little knowledge on the reasons why. In the case study, energy use behaviour of the tenants was observed in order to get a picture of the actual energy performance after the retrofit (Section 4). The observations on energy use behaviour are based on energy measurements and comfort surveys in the case study house before and after sustainable retrofit. This is put into the context of a survey on energy use patterns in the identical social housing in the area (13 households).

According to Uitdenbogerd *et al*. (2007), the most important personal (internal) determinants that relate to energy use are the age of occupants, type and age of the house, household type, education, income and the employment situation. External determinants are related to the context: access to financial resources and services, price measures and regulatory measures. The case study focuses on personal determinants. In the context of this study, it was not possible to carry out a large sample on energy use behaviour, but the observations are used to understand the actual energy performance of the building and to indicate areas for further research.

Energy and planning policies tend to focus on investment behaviour, whereas what happens after the energy measures are adopted is often ignored (IEA, 2008; Bergman *et al*., 2009; Tambach *et al*., 2010). Policy discussion (Section 5) follows the recommendation of Egmond and Bruel (2007) who state that instead of the current "instrument orientation", policies should be drawn from the identification and removal of barriers (identified in Sections 3 and 4). It should be considered that the policy developments described in this paper are subject to change and based on the situation in 2009/2010.

3. Technical Measures and the Retrofit Process

The retrofit strategy provided substantial improvements to the thermal performance of the external fabric of the house, changes to the building services and the introduction of micro-renewables (Table 1 and Figure 1). It improved the case study's energy performance rating (Energy Performance Certificate, EPC) to "A" and aimed to reduce the annual carbon dioxide emissions to below 17 kg m^{-2} $year^{-1}$ and primary energy consumption to below 115 kWh m^{-2} $year^{-1}$. EPC's are part of the UK's government commitment to the European Energy Performance of Buildings Directive. EPBD2002/91/EC came into force on 4 January 2003. They provide from "A" to "G" energy efficiency rating of a building, "A" being the best performance. Since October 2008, an EPC is now required in the UK for all homes, commercial and public buildings when bought, sold, built or rented. An air permeability value of 5 m^3 h^{-1} m^{-2} was targeted after a pressurization test was conducted, according to which the measured air permeability of the dwelling was 13.58 m^3 h^{-1} m^{-2} under a pressure of 50 Pa. In order to achieve a tighter building envelope, and an "A"-rated performance for the case study house, the following measures were considered necessary and applied (Figures 2 and 3).

3.1 *Building Fabric*

The existing external render in the ground floor and cladding in the first floor were removed, revealing the steel structure. High levels of insulation were added to the walls (over the vapour barrier), and the walls were re-rendered. Additional insulation was placed in the roof and the parts of the ground floor, which were not suspended and not of solid construction. About 200 mm of phenolic foam was applied to the walls (U-value of 0.12 W m^{-2} K^{-1}) and 350 mm of mineral wool in the roof (0.12 W m^{-2} K^{-1}). About 25mm of Aeorogel was placed under the floorboards in the hall, the living room and the dining room (0.43 W m^{-2} K^{-1}).

Table 1. Technical information about the property prior to the retrofit

Build date	1947
Floor area (m^2)	86
Construction	BISF (British Steel Association) pre-fabricated
Roof type	Pitched DECRA roof (renovated 2001)
Loft insulation (mm)	150
Wall type	Metal sheet cladding (1st floor) and painted render (ground floor)
Front and back door	Timber (installed 1992/front and 1996/back)
Windows	PVCu double glazing (installed 1997)
Heating system	Vaillant Ecotec Plus 831 Gas Condensing Combi boiler, A-rated (installed in 2009)
Retrofit team	PRP Architects, Hill Partnerships, Cambridge City Council, Cambridge University, Department of Architecture

The case study house in Trumpington before the retrofit (09.03.2010)

The case study during the construction (14.06.2010)

The house during the open day (15.07.2010)

The living room during and after the retrofit (14.06.2010 and 15.07.2010)

Figure 1. Site photographs of the retrofit case study in Trumpington, Cambridge

The existing double-glazed windows were replaced with the triple-glazed ones with rigid PVC window frames (U-value of 1.1 W m^{-2} K^{-1}), in order to align the windows with the new cladding and to reduce cold bridges. The external doors were also replaced with triple-glazed (U-value of 1.5 W m^{-2} K^{-1}) security doors.

All materials and component junctions were carefully detailed at the design stage to minimize thermal bridges and to ensure the continuity of insulation. The steel frame was adjusted locally to allow new windows to be supported in line with the new cladding, which continues below the ground level to protect the concrete slab.

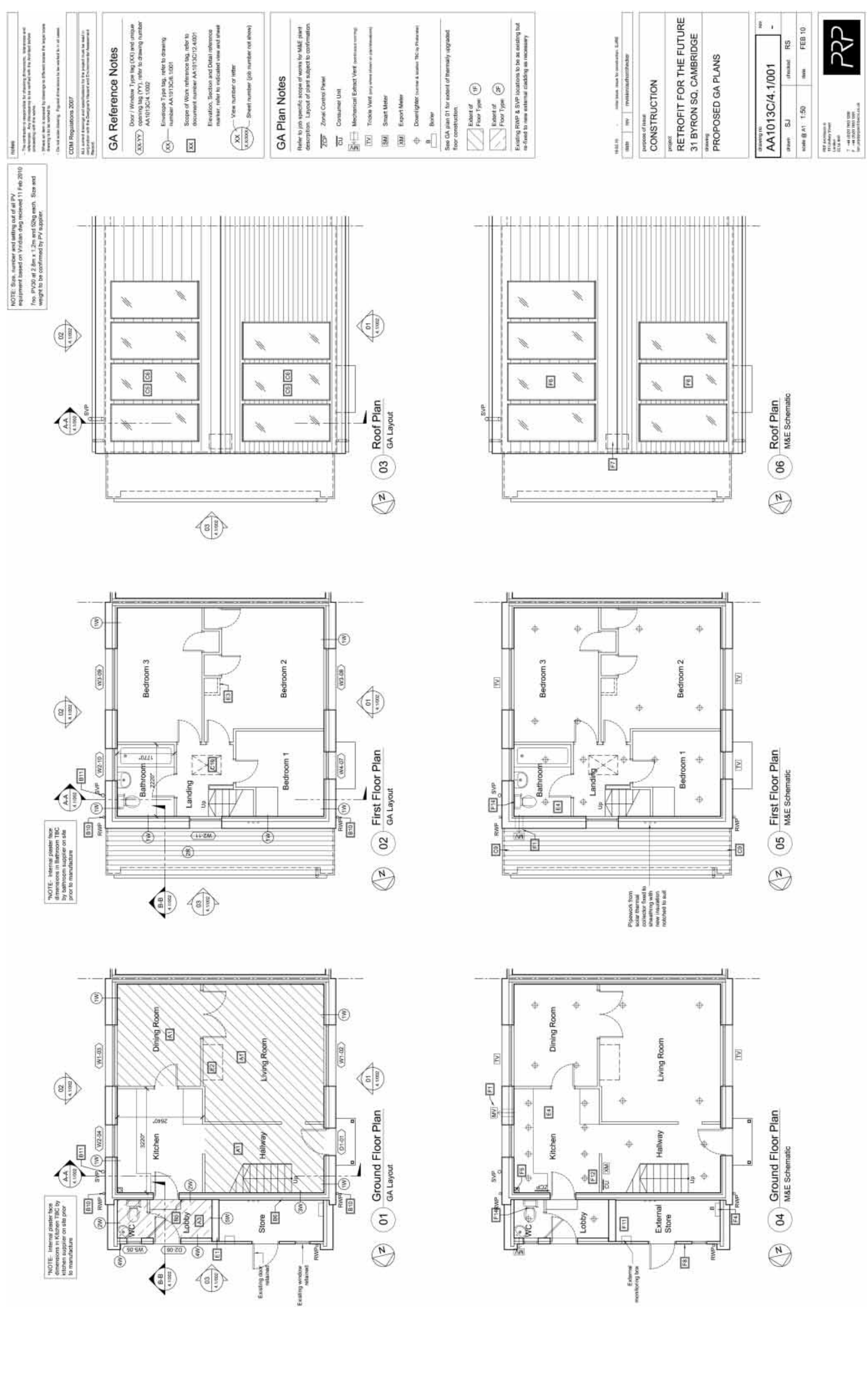

Figure 2. Proposed plans for the retrofit house

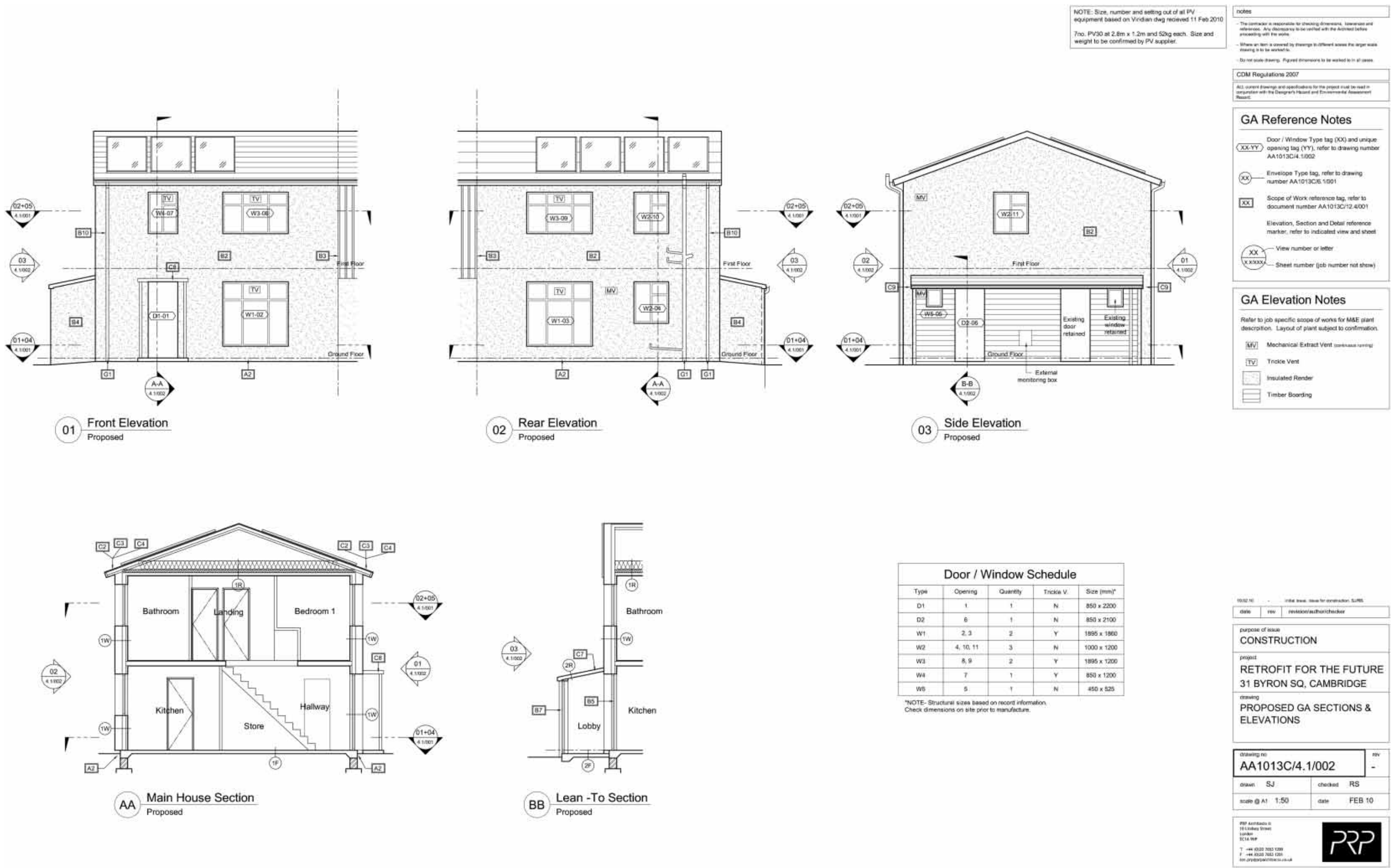

Figure 3. Proposed sections and elevations for the retrofit house

3.2 *Building Services and Micro-renewables*

In order to achieve an "A" energy performance rating, the following installations were added:

- a high-efficiency, low-emission balanced flue gas boiler (with a flue gas heat recovery) to serve the existing radiators;
- a waste water heat recovery unit to the bath and shower;
- 3 m^2 of solar collectors to provide solar thermal;
- 22.5 m^2 of polycrystalline photovoltaic (PV) systems to generate electricity;
- a mechanical extract ventilation (continuously running) with a user-controlled boost in the kitchen and the bathroom and trickle ventilators in the new windows;
- new recessed LED lighting, which required a considerable amount of work in ceilings throughout the house;
- an energy display system including an interactive touch screen interface to educate and increase the awareness of the tenants;
- "A++" energy-efficient white goods in the kitchen.

The retrofit includes an installation of seven polycrystalline PV panels with a surface area of 3.3 m^2 each (1.2 m$\times$2.8 m) and a rated output of 2.7 kWp. The PVs were placed in the optimum tilt of 32° and 20°, respectively, with no shading from the surroundings. The case study house has a west-east-oriented roof, estimated to achieve an annual PV yield of 1876 kWh, depending on the tenants' energy use behaviour and an effective load matching. In order to understand the scale of behavioural factors, two scenarios of electricity consumption were modelled with the "IES-VE" software. A scenario of an occupancy with an unemployed family with three young children (as in the case study) is compared with a working couple, including factors such as the number of occupants, the age and occupation, the heating and lighting schedule and the quantity and the use of appliances. Figure 4 shows that the differences between consumption patterns of the two household types are significant: a working couple can, theoretically, cover their energy needs with the electricity generated by the PVs fully during 5 months of the highest solar radiation (from April until August) and provide

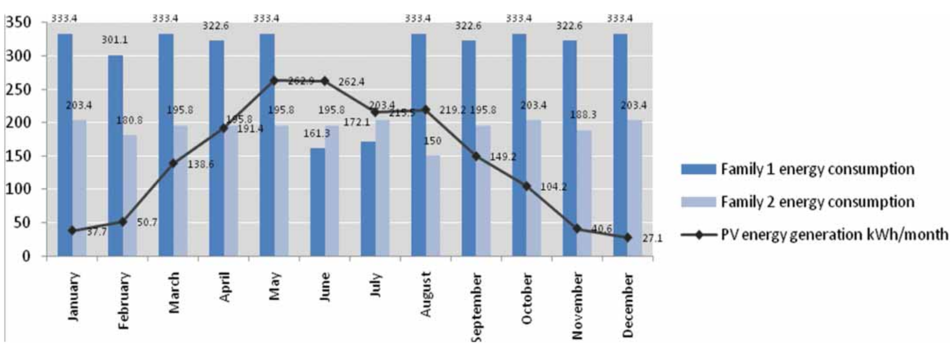

Figure 4. Comparison of electricity consumption and PV energy generation in two different household types (family 1 is a working couple and family 2 an unemployed family with three kids as in the case study)

an electricity autonomy of 82%, whereas an unemployed couple with a family can cover only 52.6% of their total electricity demand with the PVs, even during the summer.

After the installation of the PV panels, electricity generation was closely observed for 2 weeks in July 2010. According to the actual PV meter readings, the system had a mean daily generation rate of 5.6 kWh and a monthly output of 175 kWh. The electricity generation for July was 23% lower than that assumed by the simulation software, displaying a considerable difference between the projected and actual supply.

3.3 *Process*

The case study household was chosen in a competition held by the Cambridge City Council between the eligible houses for the project. According to the Home Energy Officer, the Council wanted a family who would be motivated, engaged with the retrofit and benefit from the savings in the energy bills. The construction period took 9 weeks. The construction team consisted of 12 workers and a site manager, arriving at 8.00 am and leaving at 3.30 pm daily. The tenants and their two youngest children were living in the house during the whole process. For a period of 3 weeks, the work would simultaneously occur in several places, in the kitchen, the living room and the bathroom, leaving little space for tenants and restricting them to one room. According to the tenants, the retrofit was "difficult" and "disruptive, especially after the first two weeks when the work started inside the house". Main inconveniences were a lack of private space for the family and the presence of the youngest child on the site, especially when the noise levels were high. The tenants would prefer to have been moved somewhere else during the weeks that intensive work was taking place in the house interior ("it is very important for the family either to move out during this period or to have a caravan in the garden"); this could also provide more space for workers and accelerate the construction process. Careful consultation and detailed discussions with occupiers would need to take place at the start of any such project in the future, setting out clear boundaries for both parties.

The parties involved in the project comprised the property owner (the Cambridge City Council), who initialized the project, the design team and the contractor. This was the first time a retrofit project of this scale was attempted by the owner, and the lack of experience became apparent at times during the process. The local Home Energy Officer worked closely with the design and construction team during all project stages to ensure that the final result would comply with the expectations as well as the needs of the tenants. The fact that the architect of the project and the official project manager were not locally based proved to be a drawback that caused a series of problems and a delay on the initial work schedule. The physical presence of a contractor and project designers on site is invaluable, and the use of locally based firms a wise choice in terms of efficient time and construction management.

In order to strengthen the relations between the project team and to create an open shared database, an Internet blog was introduced by the contractor. The blog mapped the progress of the construction work and included comments by different team members. At the end of the project, an open day was organized where site visits and presentations helped to disseminate the knowledge gained from the use of innovative materials and technologies, although due to the disruption to the tenants, the places were limited to the press, and political and social housing organization representatives rather than the general public.

4. Characteristics of the Household's Energy Use Behaviour

In order to get an idea of the actual energy consumption after such a retrofit, the case study was monitored using data loggers and comfort surveys before and after the construction works. Data loggers were calibrated before the study, taking temperature measurements at 10 min intervals for 24 h during 7 days, before and after the retrofit.

Pre-retrofit recordings show a large standard deviation in temperatures, indicating an unstable and a rather uncomfortable indoor environment (Figure 5). As previously mentioned, in Section 3, the tenants were an unemployed couple (aged 43 and 35) and their three sons (aged 16, 11 and 4). Although the couple spent most of the time at home, they say that they turn the heating on in winter for only 5.5 h a day at 20°C. Figure 5, however, shows that indoor temperatures are very high, indicating that the heating must have been set above 20°C, possibly at 25°C. Thermal questionnaires, which were completed by the occupants three times a day, show that the children had less tolerance for temperature change and had the highest mean comfort temperature, and they also wore less clothes than the parents at home.

The monitoring process was repeated after the retrofit was completed in July 2010 and after the wall *U*-value had been improved from 2.10 to 0.12 W m^{-2} K^{-1}. Figure 6 shows that the indoor temperatures are more stable than before the retrofit. Temperature variation during 1 day is <5°C, and temperatures measured in different rooms are closer to each other (<3°C difference).

The installation of PVs may affect the energy use behaviour; according to Keirstead (2007), the installation of PVs and system performance monitors encouraged households to reduce their overall electricity consumption by approximately 6% and shift demand to times of peak generation, but the research of Bahaj and James (2007) suggests that there is little evidence of load matching or switching in the social housing sector, especially among the high demand users. After the retrofit and the installation of the Smart Meter and the PVs, the case study family was asked whether they would shift their electricity demand during peak hours: they replied that they probably would if they noticed any

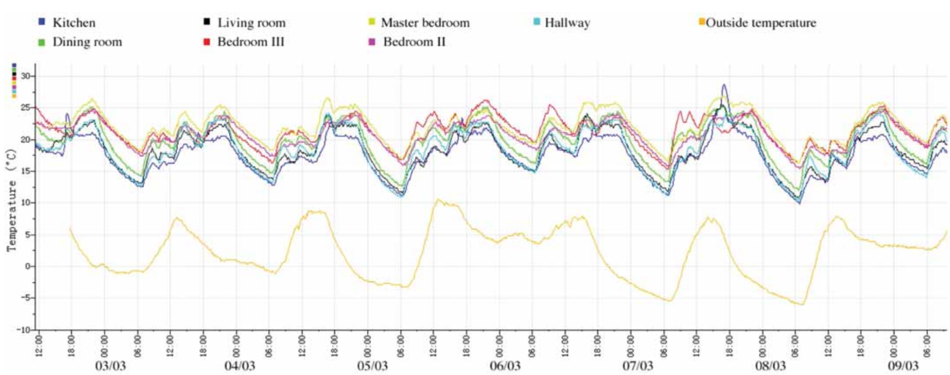

Figure 5. Pre-retrofit temperature recordings in the case study

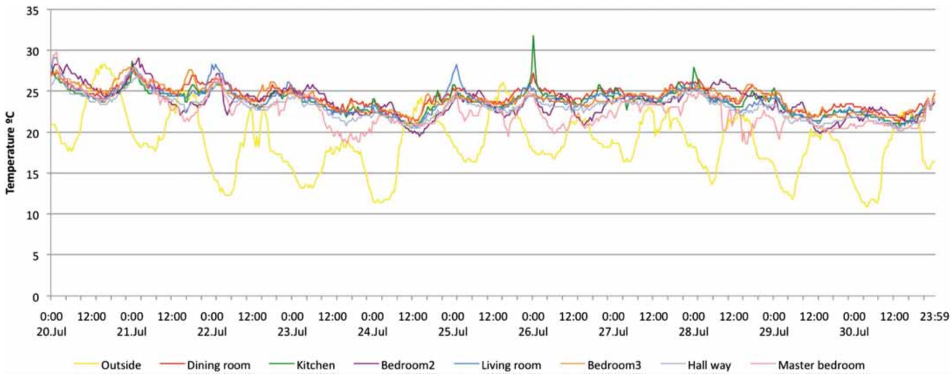

Figure 6. Post-retrofit temperature recordings in the case study

change in their electricity bills. Since there were no instructions on the PV use taking place during the interview, the tenants were not fully aware of the savings due to the load shift, nor were they able to understand the meter readings. The monitoring will continue for 2 years.

In order to better understand the characteristics of the case study household compared with other similar properties in the area, a short behavioural survey was carried out in 13 identical Council-owned properties in Trumpington. Within 13 households, 39 individuals responded to the questionnaire on heating, the use of appliances, occupancy time, level of clothing and heating habits. According to the survey, the temperature setting of the households exhibits a large variety from 16°C to 25°C, the case study being in the higher end of this scale. The number of heating hours also shows a wide range of behaviours, ranging from 5 h (as in the case study) up to 24 h per day. Due to the small sample size and time limits, it is not possible to generalize behavioural patterns, but the comfort perception of the participants does seem to differ remarkably. Further research is needed to determine the magnitude of behavioural rebound caused by the building upgrade and improved thermal performance. Moreover, a thorough study involving a larger sample should aim at a generalization of behavioural patterns and comfort perception as well as their causes.

5. Policy Strategies

After the retrofit, a Smart Meter that has a touch screen featuring an interactive graphic display connected to all the electrical appliances, the lighting circuit, the heating system and the PVs was placed. It provides an in-depth view of energy flow in the household, giving details on where most of the energy is being consumed and where wastage is occurring. At present, a PPM client who tops up weekly does not get any feedback on their energy consumption, any energy bills or annual meter readings. Driven by the 2006 EU Energy Services Directive, the Department for Energy and Climate Change has announced that gas and electricity Smart Meters will be rolled out by energy suppliers to every home in Britain by the end of 2020.

The potential impact of monthly feedback on energy use patterns is usually estimated to be 5–10% (Darby, 2006). During the first visit after the retrofit, the meter was not yet fully installed and operated in the default mode, and in the second visit, the tenants had deactivated it because of the interference with the Internet connection. The tenants expressed no interest in the meter. The fact that they had not personally invested in that technology could be one reason for the lack of motivation. Contrary to the Smart Meter, however, the tenants showed a great interest in the new "A++"-rated kitchen appliances, read the instructions and operated them successfully right after the renovation. The tenants felt more confident with white goods they were already familiar with than with the newly installed ones. Technically, Smart Meters are advanced, but the user interface of the systems leaves a lot to be desired; at this moment, the meters tend to give raw, unprocessed data in figures. As it is, many households are not even interested to programme their thermostats, and it is estimated that up to 50% of the households in the UK keep the factory settings (Pollitt, 2010). Compared with processing data from a Smart Meter, opening a window is adaptive behaviour that is intuitive and does not need data feedback—the change is expressed in the improved comfort. Previous studies have found that higher levels of education are related to less hours of using heating at the highest temperature, for example, in the Netherlands (Guerra Santín, 2010). The government policy of installing Smart Meters needs to be supported by education, especially in the social housing sector. There is a great potential in behaviour: in Britain, for every degree that the thermostat is turned down, the heat loss decreases by about 10%, and turning the thermostat down from 20°C to 15°C would nearly halve the heat loss (MacKay, 2009).

Due to high costs (nearly £6000 per installed kWp), PVs, as installed in the case study, remain unaffordable in most social housing retrofits. In order to address this barrier, the FIT for electricity came into force in the UK in April 2010. The policy requires energy suppliers to pay householders who generate their own electricity from renewable or low carbon sources. For solar power, the FIT varies from 29.3 to 41.3 p kWh^{-1}, depending on the type and size of the PV system and the date of installation, with a period that can be 25 years.

The tariffs should cover the capital cost and earn an annual return of up to 8%, in addition to the energy bill savings. Judging from the PV meter readings after the retrofit, it was estimated that the monthly economic benefit from the PVs in July will be approximately £72, with the generation tariff (FIT) of 41.3 p kWh^{-1}. This will fall by approximately 81% during the winter months. Based on the simulation, the households should be able to get up to half of their electricity from PVs and thus for free, resulting at an annual saving of around £775. In the case study, the benefit of any extra electricity sold to the grid will go to the owner, the Cambridge City Council. If a household is categorized as fuel-poor, a tenant could gain the profit from selling any surplus electricity to the grid. Such an economic incentive could trigger their interest in the system efficiency, promote load matching and, in the long term (if combined with appropriate education and feedback), lead to a behavioural change—and from a broader perspective contribute to social cohesion in deprived areas. In this case, however, there is a need to consider capital funding of PV array.

Like the case study household, in total, 12% of all energy customers in the UK (mostly low income or in debt) households are on PPMs and pay higher energy prices than if they were on a contract. Data from Brutscher (2010) show that PPM households like to make frequent and small top-ups regardless of the increased energy tariffs or income level, possibly due to liquidity constraints and loss aversion. In the case study area, families topped up their meter with around £20 weekly during the heating season. There was no indication on speculation on increasing energy prices or interest rates. Therefore, the theory of Uitdenbogerd *et al.* (2007) that energy-relevant household behaviour seems to be of habitual character rather than rational seems to be correct at least in the context of this case study.

6. Conclusions

This paper investigated the implementation of an energy-efficient retrofit in social housing and the related energy use behaviour in a case study in the UK. The conclusions are drawn based on the on-going "Retrofit for the Future" project funded by the TSB.

The energy-efficient retrofit, which improved the building to an "A" level energy performance rating, provided the occupants with a more stable and satisfactory indoor thermal environment and a lower energy bill. This was achieved by increasing thermal insulation and air-tightness levels (Section 3) to minimize the heat loss and cold bridges from the building envelope, supported by the installation of an energy-efficient boiler, PVs, LED lighting and "A++"-rated white goods. The other similar BISF houses owned by the City Council in the area will follow the example of the case study house and be upgraded in a similar, although less complicated, strategy based on the experience gained (i.e. leaving out the replacement of the existing double-glazed windows and the kitchen refurbishment to save both time and costs). The additional insulation and the LED lighting seem to be more robust, cost- and time-effective measures and do not "require particularly green tenants". Despite the FIT and the Renewable Heat Incentive, PVs and solar thermal systems remain expensive technologies for social housing and require special briefing for occupants.

Despite their original motivation, the tenants found the retrofit process difficult and disruptive. The long duration of the retrofit was considered as a barrier also by the design team, who commented that in future projects, the length should be decreased, while the occupants should be clearly informed in advance how the process is going to affect them. Further training for the planning authorities and more accurately priced costs by the contractor were two other important points of improvement.

The results support the research of Guerra Santín (2010) that the quality of building construction plays only a limited role in determining an actual energy performance in domestic buildings. The survey of households living in a social housing identical to the case study exhibited a large variety of heating patterns (Section 4). This was due to different lifestyles, occupational patterns and comfort expectations and independent of the buildings' physical characteristics. For example, families with the highest energy demand in the survey heat up their house more than three times longer than the family with the lowest energy demand. Households can use three or more times as much energy for heating as their neighbour, even if they lived in identical homes (Gram-Hanssen, 2010). Social housing may be especially heating-intensive since inhabitants, if unemployed as in the case study, tend to spend a lot of time at home. The unstable energy consumption habits in similar houses suggest two things. First, sufficient deviation in comfort temperatures should be allowed after a retrofit, more than what the standards of conventional comfort theory may indicate. People tend to be more tolerant in their comfort zones if they know that they can control the temperature and ventilation, so retrofit strategies should offer adaptive opportunities and not be over-engineered. Secondly, it is very hard to estimate standard energy consumption for even identical buildings in simulations or policies related to retrofit. Lifestyle changes have been found to be more effective than increasing the thickness of thermal insulation (9% reduction) as a means to save energy (Shimoda *et al*., 2003). When a building's thermal properties are improved, tenants may opt for different indoor thermal conditions (e.g. higher indoor temperatures), which can cause a rebound effect in energy consumption (Guerra Santín, 2010). This calls for further research, and finding out long-term behavioural patterns is the focus in the further monitoring of the case study that will continue until 2012.

The case study demonstrated the challenge of reaching the savings in the existing housing where nearly every house, budget, occupants and the design team are different. According to Boardman (2007), 80% cut in CO_2 emissions by 2050 requires a radical new approach.

General barriers to energy efficiency that remain after the retrofit are high thermal comfort standards, high occupancy and an increasing number of (entertainment) electronic appliances. It should be noted that these barriers are not technical or mechanical but cultural and may offset energy savings from technical measures, unless energy and planning policies recognize the importance of energy use behaviour. While there is a general agreement that occupant behaviour is a major determinant of energy use in buildings, assessment of the potential reduction of CO_2 emissions with non-technological options has been limited and the potential leverage of policies over these is not well understood (Levine *et al*., 2007). In the case study, despite being a fuel-poor household and PPM clients who end up paying more for their energy, the tenants' energy use is characterized by high indoor temperatures (reaching 25° during the heating season) and a significant number of entertainment appliances, every member of the family has a TV set—children even have their own mini-fridge. Despite economic constraints, there seems to be an acceptance of energy wasting behaviour that is passed on to the next generation who has even higher expectancy of comfort. Policy instruments such as FIT and Smart Meters are based on the rational choice models that assume that people make rational decisions, but in practice, there seems to be irrational economic behaviour. Furthermore, there was a lack of interest in feedback technology; the tenants became instantly confident with the new electrical appliances, but did not interact with the technology unfamiliar to them, such as PVs and the Smart Meter (Section 5). This indicates the need for support in the use of new equipment without precedents if the government policy of Smart Meters is to be successful.

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