基于模拟分析的住宅低碳改造设计
MODELLING-BASED LOW CARBON RETROFIT HOUSE DESIGN
——威尔士地区案例研究
—Case Studies in Wales, UK

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摘要

本文介绍了用于住宅低碳改造前期准备的3个动态模拟案例，包括一栋1919年前建的联排住宅，一栋1970年代和一栋2000年代建的半独立住宅，均位于英国南部威尔士地区。各案例分别检查了其改造前的性能状况，并对不同改造策略的节能与减碳潜力、经济收益进行了预测，以评选出最为可行的改造方案。决策过程综合考虑住宅改造所需费用和工程进度。本研究是SOLCER项目的一部分（SOLCER全称为低碳能源区的智能运作）。该项目鼓励本地的、新兴的低碳技术和产品的应用，作为威尔士地区高水平建造技术的示范，因此本研究的改造策略也考虑了新的节能产品和绿色技术的应用。研究发现围护结构优化手段可以极大的改进保温较差的住宅的能耗性能。太阳能光电板的应用可以满足90%的用电需求，同时提供部分家用热水。基于设备系统的改造手段在降低用能需求的同时，结合可再生能源供应和电池储能，可降低90%的净碳排放量，运行费用的降低以及可再生能源发电与输出所获得的经济补偿可节省年花费200%。总的来说，改造开始前开展的诸多工作，旨在根据不同住宅的需求选择适宜的改造策略。

本文目的在于介绍威尔士地区的住宅改造实例，这些改造方法和技术具有可复制性，并且经济可行，有望获得推广。本文希望以此为中国的住宅节能改造提供参考，尤其是涉及有关改造策略的评估，最适宜的策略组合的筛选，本地的、新兴的威尔士技术和产品的介绍等方面。

关键词

低碳 住宅改造 模拟

1 概述

住宅用能约占英国用能总量的29%(DECC, 2014a)，为满足英国政府提出的2050年减碳80%的目标(HM Government 2008)，降低与住宅相关的二氧化碳排放至关重要。据统计，英国每年只有约1%的住宅被翻新(DRCCG 2008)，据此可推算出2050年70%的英国现有住宅仍将在使用(SDC 2007)。与欧盟法规要求相一致，英国政府要求英格兰地区所有新建建筑2016年必须达到零碳(Zero Carbon Hub 2013)，威尔士地区则要求2019年实现零碳。然而，新建建筑的碳排放未来只占很少的一部分。面对全球气候变暖的趋势，有必要改造已有住宅，对其性能进行优化，提高其可持续性。

适宜的改造策略可以极大的减少住宅能耗及由此产生的二氧化碳排放。如阁楼地板保温的做法性价比高，是改造策略里最可行的手段之一。现有的英国标准要求阁楼处保温至少270mm厚 (BRE 2014)。英国绝大部分住宅采用空心墙结构，2004年的数字显示其中60%的住宅有保温层(EHCS 2004)。通过在空心墙内部填充保温材料可以降低墙体传热损失高达40% (EST EEBPH 2003)。老房子一般采用实心墙结构，需要增加外保温或内保温来优化其节能性能。据估计，经屋顶和墙体改造将一栋保温较差的老房子提高到90后标准可减少50%-80%的传热损失(Roberts 2008)。地板保温，其改造过程可能产生诸多干扰，只有对楼板主体进行改造时具有经济优势(BRE 2005)。改进气密性的关键在于降低通风热损失(Everett 2007)。英国约克地区有案可寻的四个代表性住宅的改造结果显示，通过安装新的木框门窗，对架空木地板进行密封处理，修补石膏瑕疵，可以减少60%-70%的空气渗透，若再考虑增加门窗保温可平均降低采暖能耗35%(Bell and Lowe 2000)。

本文介绍了用于住宅改造前期准备的三个动态模拟案例，包括一栋 1919年前建的联排住宅， 一栋1970年代和一栋2000年代建的半独立住宅，均位于英国南部的威尔士地区。各案例分别检查了住宅改造前的性能状况，对不同策略的节能与减碳潜力、以及可能获得的经济收益进行了预测，评选最为适宜的改造方案。决策过程综合考虑了改造费用和工程进度。本研究是SOLCER项目的一部分（SOLCER全称为低碳能源区的智能运作）。该项目鼓励本地的、新兴的低碳技术和产品的应用，作为威尔士地区高水平建造技术的示范，因而研究所涉及的改造策略也考虑到新的节能产品和绿色技术的应用。本文的目的在于介绍威尔士地区的住宅改造实例，这些改造方法和技术手段具有可复制性，并且经济可行，有望获得推广。本文希望以此为中国的住宅节能改造提供参考，尤其是涉及有关改造策略的评估，最佳策略组合的筛选，本地的、新兴的威尔士技术和产品的介绍等方面。

1.1 威尔士地区住宅改造和SOLCER项目

了解已有住宅改造的减碳潜力对于实现英国政府2050年减碳80%的目标至关重要。现有住宅中有32%建于1919年前，均为实心墙结构（图1）。1983年以来，威尔士地区所建住宅仅22%考虑了节能。已有的低碳和零碳研究基本上是针对新建建筑，考虑到2050年现有住宅绝大部分仍将在使用，有必要进一步研究改造过程中围护结构性能优化、居民行为和可再生能源技

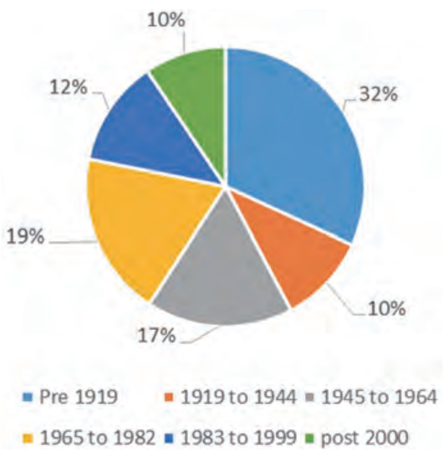

图1 威尔士地区住宅房龄分布比例（VOA 2014）

术应用等方面的复杂性(Fawcett 2013)。

本研究是卡迪夫大学威尔士建筑学院低碳研究所（LCRI）SOLCER项目的一部分，该项目旨在探索已有和新兴低碳技术的系统化实施。该项目在示范新兴技术的同时，对其大范围应用过程中遇到的助力和阻力也进行了研究。此外，该项目还与建筑工业企业紧密合作，以期为进一步发展本地低碳产业提供机会。

1.2 改造策略

本研究所涉及的改造策略包括已有和新兴的低碳技术，如围护结构保温，LED照明，无玻太阳能空气加热器（TSC）(Brown et al. 2014)，机械通风热回收系统（MVHR），和可再生能源技术如太阳能光伏发电，等等。这些策略通过一种基于设备系统的改造方法进行设计组合以优化住宅整体的节能性能。

采暖能耗占英国住宅用能总量的66%(DECC 2014b)，因而本文提及的改造策略相当一部分是为了减少住宅的采暖用能。其中，增加围护结构保温对于保温较差的住宅来说最为有效。它通过减少围护结构热损失，和改进住宅气密性以降低通风热损失，可以极大地减少住宅的采暖能耗。在改进围护结构性能的同时有必要更新住宅采暖系统，如缩小系统规模或更换新的、更为节能的设备系统，尤其是考虑到过去30年中燃气或燃油锅炉的巨大改进，效率可以从65%提升到90%多(Everett 2007)。无玻太阳能空气加热器，也叫太阳能采暖墙，是通过将一块喷涂的带孔钢板附于南向墙体或屋顶组成的太阳能空气加热系统。钢板外侧因吸收太阳能温度升高，空气首先经此外表面加热，然后在穿过孔洞以及在钢板与墙体或屋顶组成的空腔中流动时被孔洞边缘和钢板内侧表面进一步加热。若设计得当，其集热效率可达到70%以上(Brunger et al. 1999)。机械通风热回收系统通过在进出空气间设置反向热交换器而实现能量回收。它可以提供免费采暖和制冷以降低建筑的用能需求，同时供应新鲜空气和调节室内气候以改进室内热舒适性和空气质量。

除了减少采暖用能，本研究还关注如何降低住宅用电，以及通过应用可再生能源技术来满足这些需求。与常规的白炽灯相比，LED照明至少可以节能80% (DoE, 2014)，并且使用寿命较长，所需维护较少。据估计，英国的年平均太阳能资源为101W/m² (Burnett et al. 2014)，也即2.4 kWh/m²/天。考虑到太阳能集热系统在热水储存和运输过程中所损失的大量热量，太阳能光伏发电更具优势。这同时也因为太阳能集热系统需要有空间来安置热水箱，而威尔士地区家用锅炉普遍使用的combi系统并不带热水箱，因而太阳能集热系统通用性较弱。对于太阳能光伏发电系统，PV屋面所发电能可就近为家用电器和照明供电，若住宅使用系统锅炉（带热水箱），这部分电能还可通过热水箱中的电加热器提供家用热水，最后将剩余电能全部输入电网，形成一个低碳能源系统。

2 研究方法

改造前期有必要对各设计选项进行快速检查和对比。建筑模拟不失为一种有效手段，可以预测节能、减排和费用节省等性能优化效果。图2为基于动态模拟的住宅低碳改造设计示意图。模型的搭建应基于模拟对象的具体信息以确保模拟结果的准确性。建模所需信息包括气候数据、场地位置和周边环境、建筑尺寸和围护结构构造、室内设计条件等。在改造过程中，随着越来越多的信息得到核实和确认，模型应相应地作出调整以获得更为确实的模拟结果。另外还应对改造后的建筑性能进行监测，从而调整和优化建筑模型。由于目前只能获得开始两三个月的监测数据，本

Abstract

This paper describes three case studies of dynamic simulation in preparation for the low carbon retrofit practice, namely, a pre-1919 terrace house, and a 1970s and a 2000s semi-detached house. The houses are located in Wales, UK. Each case study examines its current performance, assesses the effectiveness of different retrofit strategies, and evaluates the best group of options available. Retrofit cost and time schedules have also been taken into account when making the decision. As a part of the SOLCER (Smart Operation for a Low Carbon Energy Region) project, local and emerging low carbon technologies are encouraged to be used as a demonstration of advanced Welsh construction technologies, and therefore have been considered in this research. It was found that a fabric approach could greatly optimize the energy performance of a poorly insulated house. The application of PV has been shown to reduce the total power demand from the grid by around 90%, and also contributing to domestic hot water heating. A systems based approach has been adopted, combining reduced energy demand, renewable energy supply and battery storage to reduce net carbon emissions by up to 90%, saving total cost by over 200% through operating energy cost reduction and cost earnings for renewable energy generation and export. Above all, great effort has been made to tailor the best retrofit approaches to meet requirements of different properties before starting work on site.

The purpose of this paper is to describe the domestic retrofit case studies in Wales, which are intended to be replicable and affordable for large-scale application in the future. It hopes to provide some reference to energy-led domestic retrofit programmes in China in relation to the approach to assess the retrofit strategies, identification of the best approach available, and the introduction of new technologies and local Welsh products.

Key Words

Low Carbon; Retrofit House; Simulation

文将不涉及这部分内容。

改造前开展的一系列调查便于探讨潜在障碍和问题的解决办法，以及如何有效地实现项目目标的方法和手段。改造方案基于改造前的住宅状况进行设计和建议，或通过优化围护结构性能的手段，或采用基于建筑设备系统的方法，亦或是两者的综合。一般认为低碳住宅设计遵循如下设计程序：首先降低室内热负荷，其次进行被动式设计，并采用有效的建筑设备系统，最后整合可再生能源系统为建筑供能(Jones et al. 2015)。由此可见，围护结构的优化是优选改造策略的第一步。改造策略主要包括外墙保温、阁楼保温、low-E双玻、LED照明、TSC、MVHR和太阳能光伏屋顶。研究同时考虑了策略实施所带来的附加影响，包括因围护结构性能优化所改进的房屋气密性、外墙新增保温层所产生的遮阳作用、外墙内保温降低的采暖面积。在此基础上，研究模拟和评估了不同设计方案所带来的节能与减碳效果，以及相关的经济收益，最后通过比较这些潜在益处，并综合考虑预算和时间因素，确定最终的改造方案。

本研究所用软件包括HTB2、VirVil SketchUp (Jones et al. 2013) 和Excel。HTB2与VirVil SketchUp均由卡迪夫大学威尔士建筑学院研发。HTB2是一款较为典型的高级数字模拟工具，通过输入场地逐时的气候数据、建筑材料和构造、空间分布、设备系统运行和人员在室等信息，来计算室内达到一定热舒适性水平所消耗的能量 (P.T. Lewis, D.K. Alexander 1990)。该软件使用灵活并且易于调整，适用于快速更新的建筑节能和可持续设计领域。该软件已研发30年，经历了一系列的扩展性测试和认证，包括IEA Annex 1 (Oscar Faber and Partners 1980)、IEA task 12 (Lomas 1994) 和IEA BEST-EST (J. Neymark et al. 2011)。VirVil SketchUp是HTB2用于规划尺度模拟的外延开发。它通过连接SketchUp与HTB2可以进行社区和规划层面的多建筑动态热模拟，该模拟综合考虑了周边环境所带来的遮阳影响。

图3所示为一次完整模拟的流程图。首先，VirVil SketchUp被用来生成住宅门窗的遮阳罩。该信息和其他包括气候、位置、围护结构构造等在内的信息一起输入能量模型，在HTB2中进行热工模拟，模拟结果通过Excel显示与处理。这部分模拟用于计算住宅的采暖用能和可再生能源潜力，也即太阳能光伏发电量。包括家用热水和用能在内的其他能量需求可根据场地信息或参考有关规范和数据库进行估算。太阳能光伏发电通过与不同的设备系统连接可满足部分或全部的用电需求。燃气消耗总量则通过计算提供剩余家用热水所需的燃气

图2 基于模拟的住宅低碳改造设计图示

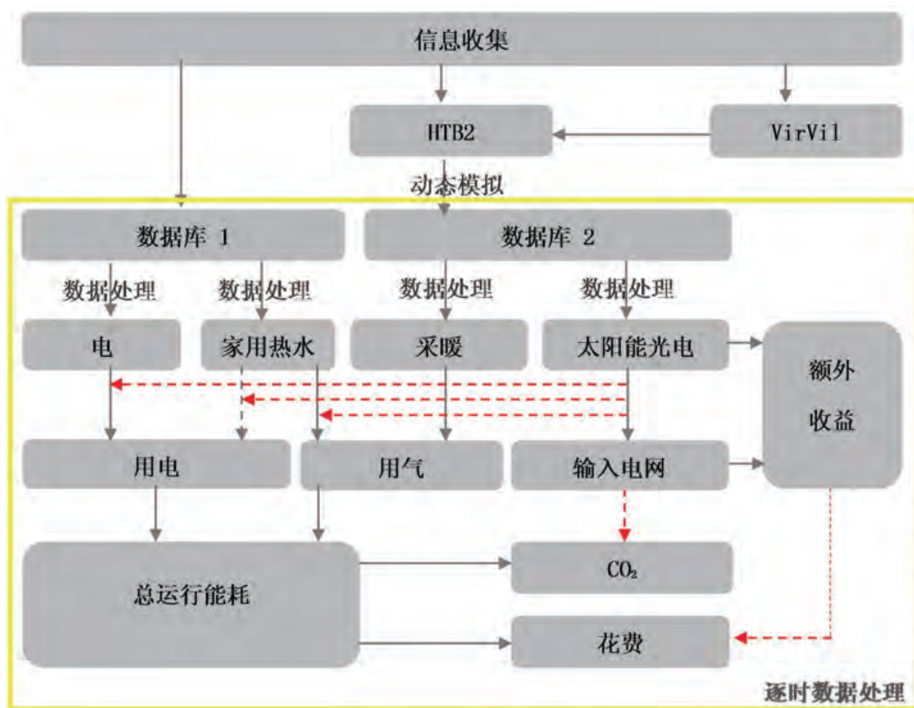

图3 模拟流程图

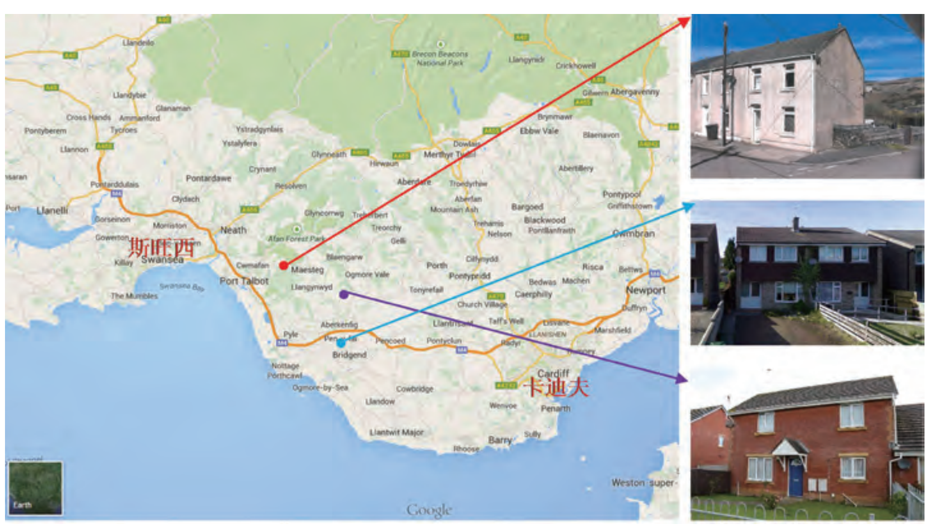

图4 各住宅位置分布

量和住宅采暖所需燃气量的总和获得。若用电烧水如使用电热水器，应从燃气消耗中减去该部分能量，并将其加入电能消耗中。最终的用电量应是所有用电需求的总和减去可再生能源发电供应的部分。

在前面所得的运行能耗数据的基础上可进行相关的碳排放和费用计算。例如，能源消耗量乘以碳排放因子可获得对应的碳排放量(BRE 2014)，而向电网输出的电能可视为产生负碳排放。运行费用可根据网上的最新燃料价格直接计算获得。研究同时考虑应用太阳能光电系统所带来的额外收益。这部分收益源于英国政府的可再生能源发电补偿计划（FITs），该计划旨在推动可再生能源和低碳发电技术的小范围应用。无论电能最终由居民自己消耗还是输入电网，每生产一个单元电能可获得一定量的经济补偿。不仅如此，向电网输出电能还可获得输出补助。家用光伏发电系统的最大输出功率一般不会超过30kW，因而不需安装价格昂贵的智能电表，常规认为将有50%的光伏发电量流入电网。

3 模拟条件

研究案例均位于英国南部，威尔士首府卡迪夫与斯旺西之间（图4）。模拟所需数据如下：

(1) 气候数据。HTB2只接受meteorological的文件类型，该类型文件可通过HTB2中的气象 文件转换器转换得到。各住宅的原始气象数据为EPW文件，均由meteo-norm V7.1.1.122 软件生成。

(2) 建筑模型。建筑模型包括两部分，住宅尺寸和建筑围护结构构造。表1为各住宅的基本建筑信息汇总，由来自建筑产业的专业人士现场调研获得。

(3) 室内设计条件。即与建筑设备系统相关的信息，包括采暖，通风，室内得热（人员、照明、其他家电）。这些信息或经由现场调查如空气压强测试，或参考常规的典型情景模式（表2）获得。

(4) 改造策略。请见下一部分有关各住宅改造策略和模拟方案的具体介绍。

(5) 碳排放因子（表3）。

(6) 燃料价格和补偿价目（表4）。

4 性能优化预测

4.1 住宅一

根据围护结构优化先行原则，综合考虑改造前的住宅状况（表1），住宅一设计采用如下改造策略，

a) 100mm外墙外保温所有外墙

b) Low-E双玻

c) 300mm阁楼保温，50mm平屋顶保温（背面加建）

d) LED照明

e) MVHR - Energisaver 280全住宅系统

f) 太阳能光伏屋面（2.5 kWp，光电转换效率14.4%），铅酸蓄电池（4.8 kWh, DoD 50%）

g) 节能系统锅炉，带浸入式电加热器的热水箱

图5为设计的低碳设备系统示意图，采用太阳能光伏屋面所发电能供应LED照明和提供家用热水。现场作业前开展的诸多模拟（表5）旨在考察不同改造策略和方案的节能与减碳潜力，及可能带来的经济效益。模拟涵盖从围护结构的性能优化到进一步的设备系统更新以展示改造各阶段所达到的优化效果。

模拟结果显示（图6、图7）：

(1) 围护结构优化可减少69.2%的燃气消耗，降低48%的碳排放，节省43%的运行费用。

(2) LED照明可降低电耗18.8%，但LED照明所产生的室内得热相对较少，使得采暖用能提高，从而增加了1.9%的燃气消耗，最终只能减少5%的二氧化碳排放量，节省6%的运行费用。

(3) MVHR可减少燃气消耗2%，而MVHR所产生的风机用能会增加4%的电能消耗，最

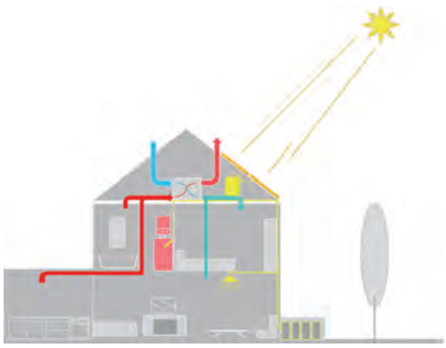

图5 低碳系统设计示意图：住宅一

表1 住宅基本信息汇总

住宅	住宅1	住宅2	住宅3
位置	1 Galltcwm Terrace, Byrn, Port Talbot, Neath Port Talbot	8 Cricklewood Close, Bridgend	13 Tyn-Y-Waun Bettws, Bridgend
类型	威尔士山谷地区典型联排式住宅，建于1919年前，两层两卧室。	半独立住宅，建于1960年代，两层三卧室。	半独立住宅，建于2000年代，两层三卧室。
建筑面积	67m²	70m²	86m²
改造前主要特征	• 主体为实心外墙 • 背面加建为不带保温的空心墙体 • 不带保温的硬质混凝土地面 • 250mm阁楼保温 • 不带保温的平屋顶(背面加建) • 单玻 • 系统锅炉	• 山墙为不带保温的空心墙体 • 背面与一层正面外墙为带保温的空心墙体 • 不带保温的硬质混凝土地面 • 100mm阁楼保温 • 双玻 • Combi锅炉（不带热水箱）	• 带保温的空心墙体 • 不带保温的硬质混凝土地面 • 150mm阁楼保温 • 双玻 • 系统锅炉

表2 住宅一般室内设计条件

空间	采暖	内部得热		
		人员	照明	家用设备
起居室	工作日： 7－9，16－23，低于20°C开始采暖； 周末：7－23，低于20°C开始采暖。	工作日：17－23, 72W； 周末：8－23, 72W	全周 17－23 110W	电视：全周 17－18 135W 20－22 158W
厨房		工作日：7－8 & 18－21 84W； 周末：7－8，12－13 & 18－21 84W	工作日7－8 & 18－21 56W; 周末7－8，12－13 & 18－21 56W,	炉灶：工作日7－8，1190W & 18－19 1700W；周末7－8 & 12－13 1190W，18－19 1700W； 冰箱：全周 0－24 60W 热水：全周 0－24 77W
餐厅		工作日：8－9，140W & 18－20 115W; 周末：8－9 & 13－14，140W & 18－20 115W	工作日：8－9，126W & 18－20 171W； 周末：8－9 & 13－14，126W & 18－20 171W	
卧室1 (主卧)		全周：0－8 &23－24, 148W		
卧室2/3 （小孩）		全周：0－9 &21－24, 38W		
卫生间		全周： 7－8, 100W 17－18, 40W 21－23, 35W	全周： 7－8, 100W 17－18, 40W 21－23, 35W	热水：全周0－24 77W
注意：经空气压强测试可得改造前各住宅的空气渗透速度（每小时的换气次数），住宅一为0.73，住宅二为0.54，住宅三为0.33。(Allen E. and Pinney A., 1990)				

表3 碳排放因子与一次能源系数

燃料	一次能源系数	碳排放因子(Kg CO_2/kWh)
燃气	1.22	0.216
电	3.07	0.519
引自 SAP 2012: table 12 (BRE, 2014)		

表4 燃料价格与太阳能发电补偿价目(FIT)

种类	价目 (p/kWh)
用气	5.13
用电	16.00
太阳能光伏发电量	14.38
太阳能光伏发电电网输出量	4.77
引自: a. British Gas: http://www.britishgas.co.uk/, 2014; b. Feed—in Tariff Payment Rate Table for Photovoltaic Eligible Installations for FIT: 1st Apr. 2014— 31st Dec. 2014 (Ofgem, 2014).	

表5 住宅一：模拟方案汇总

方案	改造策略
1	基准方案 (改造前)
2	a) b) c)
3	a) b) c) d)
4	a) b) c) d) e)
5	a) b) c) d) e) f)
6	a) b) c) d) e) f) g)

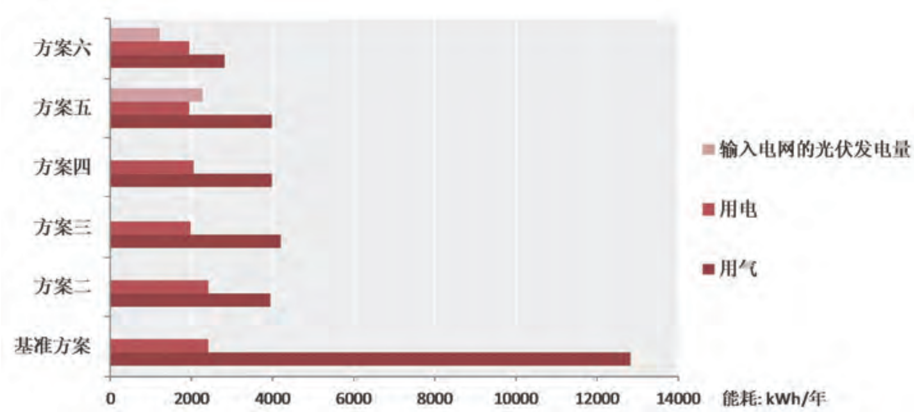

图6 住宅一：不同改造方案的用能比较

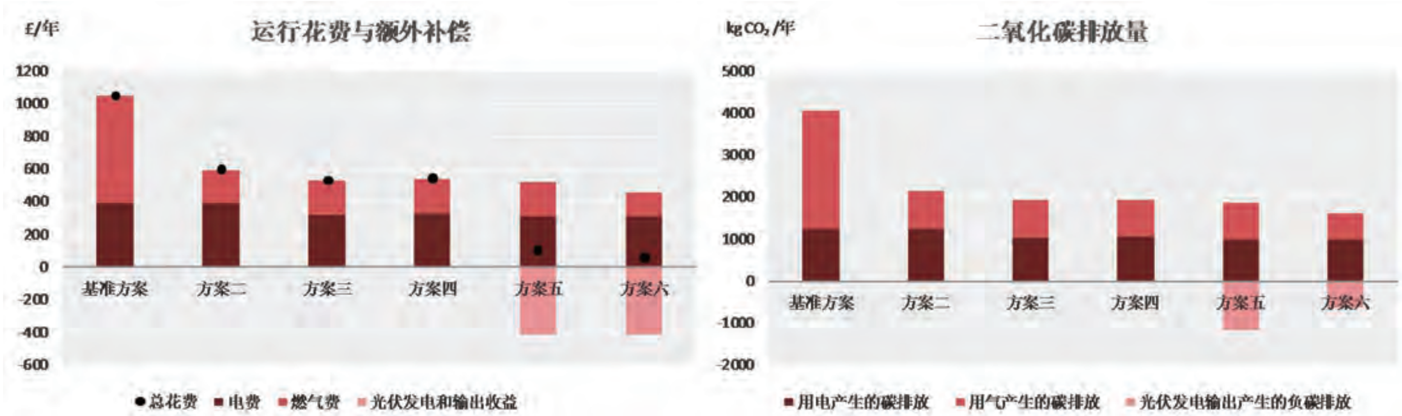

图7 住宅一： 左图为不同改造方案的运行费用和相关收益比较；右图为不同方案的碳排放量比较

终仅降低了1%的二氧化碳排放，无费用节省。

(4) 太阳能光伏发电和铅酸蓄电池供应LED照明仅减少5%的用电，90%的光伏发电量将直接输入电网，可降低净碳排放31%，综合考虑运行费用的降低和太阳能光伏发电与输出所获得的经济补偿全年花费可节省40%。

(5) 若上面的系统同时连接热水箱（方案6），44%的光伏发电将就地消耗，可以提供90%的家用热水。该方案可以在方案五的基础上，另外节省6%的花费，减少运行能耗产生的碳排放5%，而蓄电池充放电过程所产生的更多电损失会增加7%的净碳排放。

SOLCER项目鼓励可再生能源的就地使用，方案6的电能输出低于方案5，因而被选为该住宅的最佳改造方案。

4.2 住宅二

前期调研显示，住宅二只在背面和一层正面做了墙体保温，并且采用家用combi锅炉系统提供空间采暖和供应家用热水（见表1）。该住宅的改造策略设计如下，

a) 空心墙内填充50mm的保温层 （侧面山墙）
b) 50mm外保温涂料
c) 50mm的Kingspan Optimi-R外墙外保温（二层正面）
d) 300mm阁楼保温
e) MVHR - Energisaver 280全住宅系统
f) LED照明
g) PV屋面（3.0kWp，光电转换效率14.4%），铅酸蓄电池（4.8kWh，DoD 50%）

与一号住宅一样，研究建议采用综合方案。由于没有空间容纳热水箱，其低碳系统设计采用光伏发电供应LED照明和一个小型电冰箱的使用（图8）。经初步估计，这些改造策略若全部实施将超出预算，因此有必要对这些策略进行筛选。就此展开的建筑模拟旨在评估和比较不同方案的优化效果。表6对所有需要模拟的设计方案进行了汇总。

由模拟结果（图9、图10）可看出，方案4最为低碳，它应用了除MVHR以外的所有改造策略，可减少36%的燃气消耗，降低23%的用电和88%的净碳排放，同时节省110%的花费（包括了太阳能光伏发电和输出所获得的经济补偿）。此外，方案2、方案3和方案6可达到的性能优化水平和获得的经济收益接近方案4，应作为备选方案纳入最终的决策过程。方案5不包含太阳能光伏屋面和铅酸蓄电池，虽最为经济，但因并未整合可再生能源供应系统，被视为最不低碳的改造方案。

4.3 住宅三

住宅三建于2000年后，围护结构保温较好，采用的系统锅炉相对较新，带热水箱（表1）。初步设计建议如下a)至d）的改造策略，采用全系统方案利用太阳能光伏屋面所发电能供应所有用电设备，包括热水箱中的电加热器。附加策略e)至g)为预算内进一步优化所提供的建议。图11示意了各设备系统在住宅中如何工作。

a) 300mm阁楼保温
b) LED照明
c) 太阳能光伏屋面（5 kWp，光电转换效率14.4%），铅酸蓄电池（DoD 50%，全住宅供电）
d) 节能锅炉，带电加热器的热水箱
e) 50mm外保温涂层

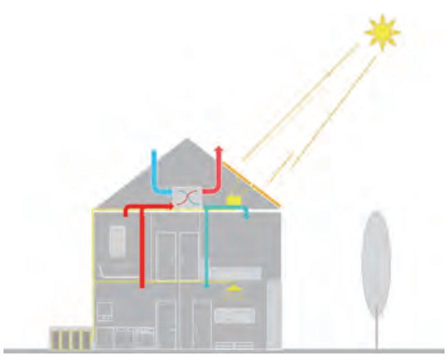
图8 低碳系统设计示意图：住宅二

表6 住宅二：模拟方案汇总

方案	改造策略
1	基准方案(改造前)
2	a) c) d) f) g)
3	a) c) d) e) f) g)
4	a) b) c) d) f) g)
5	a) b) c) d) e) f)
6	a) b) c) d) e) f) g)

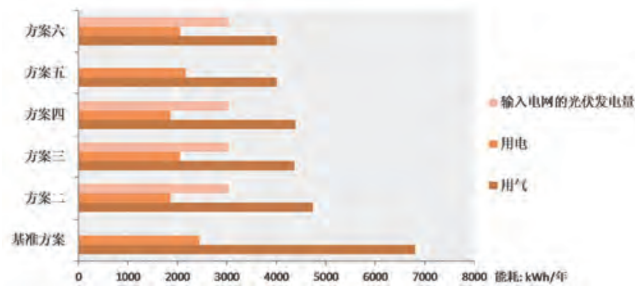

图9 住宅二：不同改造方案的用能比较

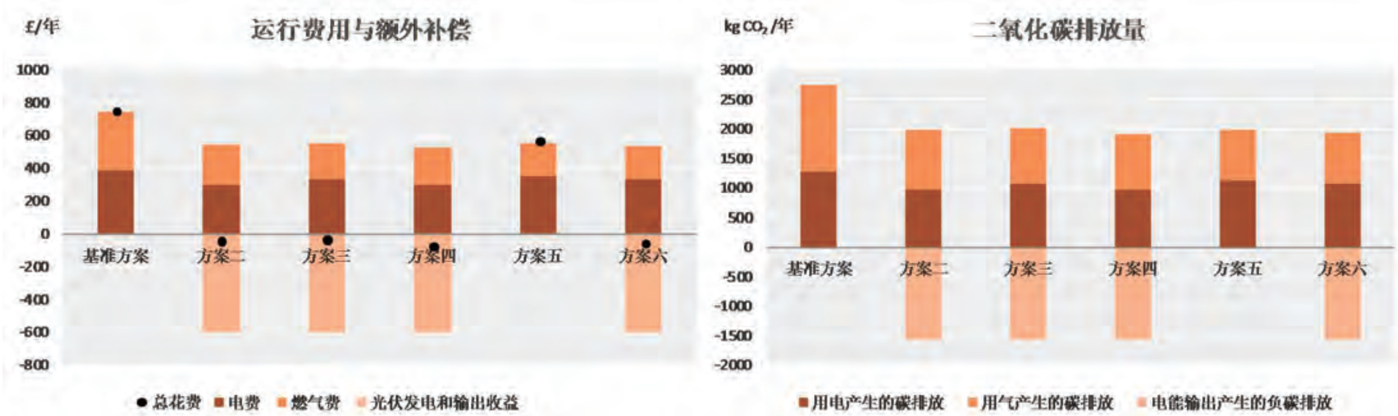

图10 住宅二：左图为不同改造方案的运行费用和相关收益比较；右图为不同方案的碳排放量比较

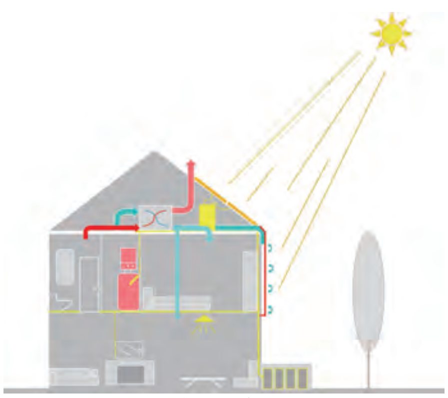
图11 低碳系统设计示意图：住宅三

f) MVHR- Energisaver 280 全住宅系统

g) 4.4m2 TSC（太阳能采暖墙）

建筑模拟的开展旨在评估改造实施进程中可获得的阶段性收益，同时对初期设计和进一步改进（附加策略）所达到的优化效果进行分析和比较，辅助最终决策。

模拟结果（图12、图13）显示：

(1) 方案4为所有初步设计策略的集合，与基准方案相比，可减少24%的用气量，降低83%的用电量，余下的1 448kWh电能将全部输入电网。该方案因运行能耗降低可减碳58%，降低净碳排放93%，因运行费用降低及光伏发电与输出所获得的经济补偿可节省总花费203%。

(2) 方案8在方案4基础上进一步优化，与基准方案相比，可降低用气46%，减少用电78%，余下将有1 330kWh电能输入电网。该方案因运行能耗降低可减碳

表7 住宅三：模拟方案汇总

方案	改造策略
1	基准方案(改造前)
2	a)
3	a) b)
4	a) b) c) d)
5	a) b) c) d) e)
6	a) b) c) d) f)
7	a) b) c) d) e) f)
8	a) b) c) d) e) f) g)

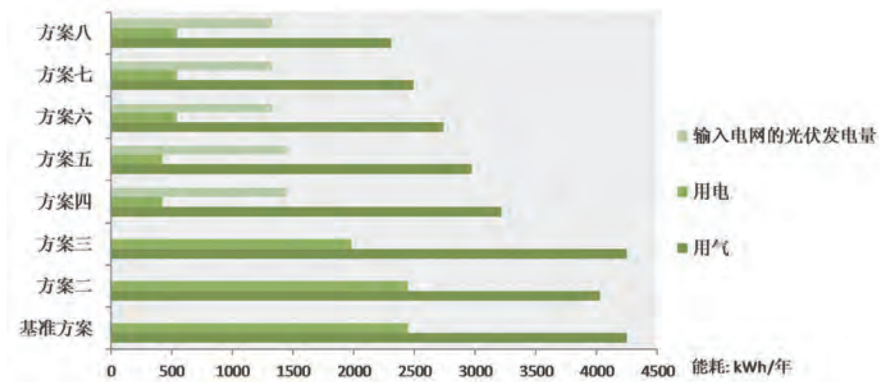

图12 住宅三：不同改造方案的用能比较

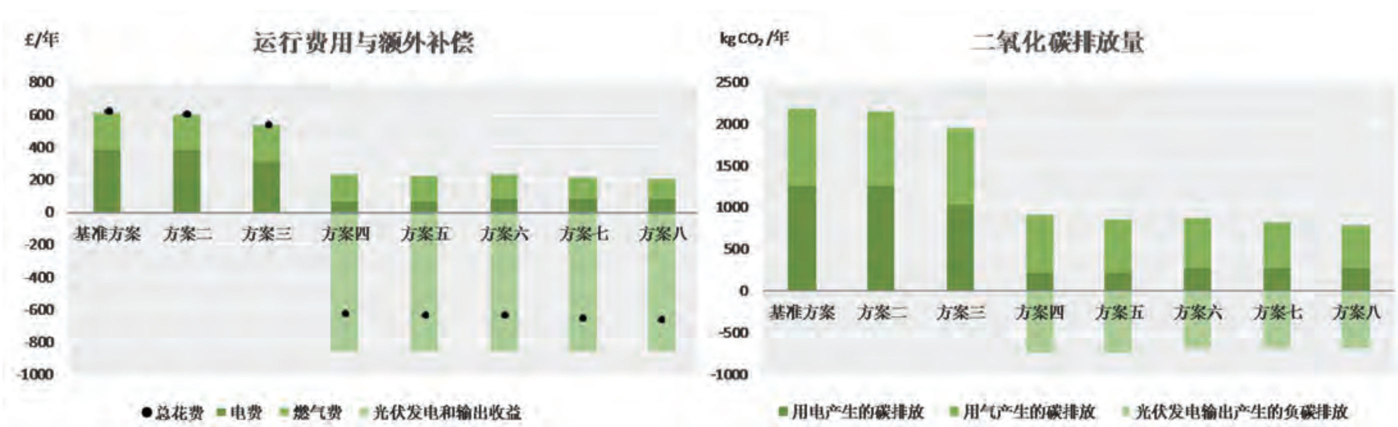

图13 住宅三： 左图为不同改造方案的运行费用和相关收益比较；右图为不同方案的碳排放量比较

64%，考虑电能输出所产生的负碳排放最终可降低净碳排放96%，节省总花费207%。

(3) 总体来说，LED照明、光伏屋顶、节能锅炉和热水箱等改造策略较为节能有效。而机械通风热回收系统（MVHR）和太阳能采暖墙（TSC）两者虽然可以减少10–15%的燃气消耗，但MVHR使用会产生风机用能，从而增加了5%的用电量。

(4) 由此可见，方案4所达到的节能、减碳效果和获取的经济效益接近方案8，故而两者都应被纳入最终的决策过程。

此外，各设备系统的性能也得到了检验。经模拟预测，在当地气候条件下，30m²、光电转换效率为14.4%的太阳能光伏屋顶可达到的最大输出功率为4.6kW。对于改造所采用的铅酸蓄电池，若设定其放电深度为50%、充放电效率为60%，综合考虑它对整个设备系统的影响及本身的费用成本（参考住宅一），选择8kWh大小的电池性价比较高。图14所示为模拟的经过TSC板的空气温度升高值与其表面太阳辐射量两者间的关系，非常接近参考数据（Conserval Engineering Inc. 2003）。

5 讨论与结论

基于以上的模拟结果，各相关团体开展了进一步的研究和讨论，综合考虑时间和预算因素，作出最终决策。由表8可见：

(1) 为住宅一建议的所有改造策略都得到了落实。

(2) 住宅二选择了方案3。由于无法获得本地产的外墙保温涂料，最终方案并不包含该项策略。经预测，对于住宅二，MVHR的使用主要是为了提高空气质量和室内热舒适性，其本身并不节能。与住宅一相比，该住宅采用了容量较大的蓄电池组，这主要是考虑其光伏屋面，同时，针对不同住宅的电池选型也是我们目前正在学习的内容。

(3) 住宅三受预算和时间因素的影响并未实施附加的改造策略。该住宅最后安装了一组为预测容量大小两倍多的蓄电池，以测试拥有较大电池容量的设备系统的性能状况。同上，在不断学习实践的过程中，每一栋住宅的电池选型会前进一步。

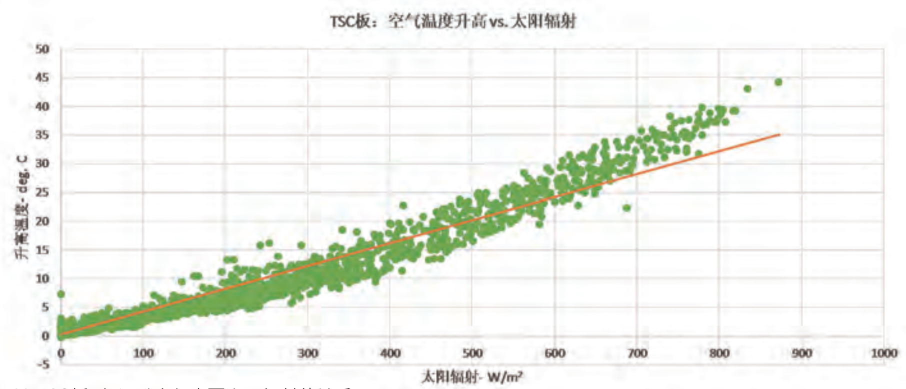

图14 TSC板：气温升高与表面太阳辐射的关系

表8 最终实施的改造方案

改造案例	住宅一	住宅二	住宅三
最终实施策略	综合方案：	综合方案：	全系统方案：
	• 外墙外保温（100mm 聚苯乙烯塑料泡沫塑料板EPS） • Low–E 双层玻璃 • 阁楼保温(300mm) & 平屋顶保温(50mm) • 机械通风热回收系统MVHR - Energisaver 280全住宅系统 • LED照明 • 太阳能光伏屋顶(2.5 kWp)+铅酸蓄电池 (4.8kWh)) • 系统锅炉 + 带浸入式电加热器的热水箱	• 空心墙内加保温 • 50mm 外墙外保温(二层正面外墙) • 阁楼保温 (300mm) • 机械通风热回收系统MVHR - Energisaver 280全住宅系统 • LED照明 • 太阳能光伏屋顶(2.7 kWp) +铅酸蓄电池(8.5kWh)	• 阁楼保温 (300mm) • LED照明 • 4.5 kWp 太阳能光伏屋顶 • 18kWh铅酸蓄电池 • 节能锅炉和带浸入式电加热器的热水箱
场地内的可再生能源系统	太阳能光伏屋顶发电以供应LED照明，并为热水箱中的热水加热提供能量。	太阳能光伏屋顶为LED照明和一小型冰箱供能。	太阳能光伏屋顶为所有家用用电设备供能，其中包括了热水箱中的热水加热。

表9 改造后住宅的全年收益预测 （英镑/年）

案例	全年节省的运行费用	太阳能发电和输出所获得的政府补助	总的年收益
住宅一	594	410	1004
住宅二	185	546	731
住宅三	389	837	1226

根据最终决策确定的信息及改造后现场调查测试的结果（气密性测试），研究对各住宅的实际改造方案进行了最终模拟。图15和表9比较并归纳了各住宅最终方案的性能优化效果。住宅三因采用全系统方案，利用光伏发电供应全住宅使用，可以达到最大的节电与减碳效率，并获得最大的经济收益。住宅一减少的燃气用量最大，其他两栋住宅由于相对较新，保温性能较好，改造前后燃气用量变化不大。

总体来说，改造前开展的诸多研究工作，旨在适应各住宅的不同需求选择适宜的改造策略，结论如下，

(1) 围护结构优化手段对于保温较差的住宅而言，节能效果明显。

(2) 常规的基于设备系统的改造方法，以住宅二采用的可再生能源系统为例，

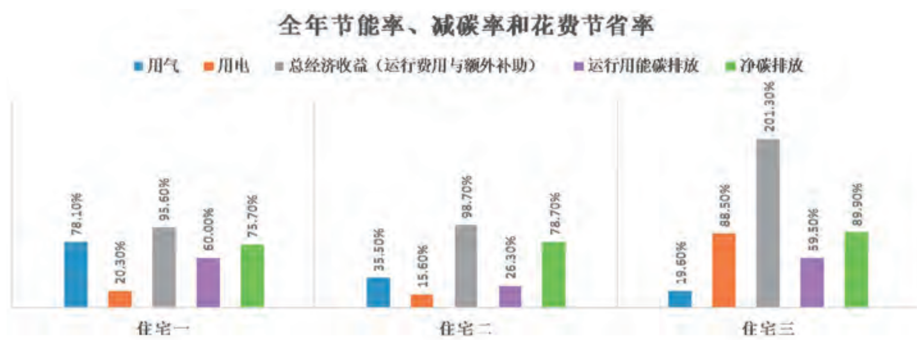

图15 最终改造方案的性能预测比较

光伏发电产生的大部分电能将直接输入电网。若增加带电加热器的热水箱（如住宅一），约1/3的光伏发电量将用于提供家用热水。而光伏发电系统若与所有家用电路连接（如住宅三），可减少90%的电网用电需求，输入电网的电能只占总发电量的1/4。

⑶ 若设计得当，基于设备系统的改造手段可减少60%运行能耗产生的碳排放，同时考虑光伏发电输出所带来的负碳排放可降低净碳排放90%，因运行费用的降低以及可再生能源发电与输出所获得的经济补偿可节省年花费200%。

6 下一步研究

下一阶段将比较模拟结果与检测数据，展开相关研究。

致谢

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1 Introduction

To meet the UK government's target of an 80% reduction in the UK's carbon emissions by 2050 (HM Government 2008), it is crucial to reduce the carbon emission associated with the domestic sector, which accounts for some 29% of the UK's total energy consumption (DECC 2014a). The housing stock in the UK is replaced with a proportion of only around 1% a year (DRCCG 2008), it is estimated that 70% of the UK's housing stock that will exist in 2050 has already been built (SDC 2007). The government target is for all new housing in England to be zero carbon by 2016 (Zero Carbon Hub 2013) and in Wales by 2019, in line with EU directives. However, the new build will only contribute to a relatively small portion of carbon emission in the future. It is therefore essential to retrofit and adapt the existing housing stock to improve their energy performance and to increase their sustainability in the face of global climate change.

Through proper retrofit strategies, energy use and the resulting carbon emissions of the existing houses can be reduced significantly. Among all, loft insulation can be one of the most easy to apply as a cost-effective measure. A minimum 270mm of loft insulation is required by the up-to-date Building Regulations in the UK (BRE 2014). A large number of domestic houses in the UK were built with cavity walls, 60% of which didn't have insulation by 2004 (EHCS 2004). By filling the cavity wall with insulation, it could reduce up to 40% heat loss through the walls (EST EEBPH 2003). Older houses have solid walls and require external or internal wall insulation to improve their performance. It is estimated that upgrading an old poorly insulated house to post-1990 standards through roof and wall improvement would reduce heat loss by 50%-80% (Roberts 2008). Regarding ground floors, the disruptive nature of retrofitting insulation means it is only likely to be economically viable during major refurbishment of the floor (BRE 2005). Improving air tightness is the key to minimising heat loss from ventilation (Everett 2007). According to findings in a documented retrofit of four representative houses in the York region in the UK, the rate of air leakage could be reduced by 60-70% through the installation of new window and door wooden frames, sealing of suspended timber ground floors, and repair of defects in plaster (Bell and Lowe 2000). This, together with improved insulation of windows and doors could reduce heating energy by 35% on average.
This paper describes three case studies where dynamic simulation has been used in preparation for the retrofit practice of a pre-1919 terrace house, a 1970s and a 2000s semi-detached house in Wales, UK. Each case study examines its current performance, assesses the effectiveness of different retrofit strategies, and evaluates the best group of options available. This process was used to aid decision making at the early stage of the retrofit programme. Retrofit cost and time schedules have also been taken into account when making the decision. As a part of SOLCER (Smart Operation for a Low Carbon Energy Region) project which is funded by ERDF, local and emerging low carbon technologies are encouraged to be used as a demonstration of advanced Welsh construction technologies, and therefore have been considered in this research. The purpose of this paper is to present the domestic retrofit case studies in Wales, which is expected to be replicable and affordable for a large scale application in the future. It intends to provide some reference to the energy-led domestic retrofit in China in relation to its attempts to identify the best approach available, the introduction of new technologies and local Welsh products, and how to meet the budget and time requirements.

1.1 Background: retrofit houses in Wales and SOLCER

When considering the UK government's target of 80% reduction in carbon emissions by the year 2050, it is important to understand the potential carbon savings available when retrofitting the existing stock. 32% of the existing housing stock is pre 1919, and as such solid wall construction (Figure 1). Only 22% of the Welsh housing stock has been built with some consideration for energy efficiency (since 1983). Most low and zero carbon research has focused on new build, but the majority of buildings that will exist in 2050 have already been built, and the complex nature of fabric improvements, occupant behaviour and renewable technologies in the retrofit design process need to be researched further (Fawcett 2013).

Research within this paper has been carried out as part of the LCRI SOLCER project, which aims to explore the implementation of existing and emerging low carbon technologies through a systems based approach. The project has demonstrated the application of new technologies and examined the drivers and barriers preventing the large scale roll out of these technologies. It has worked closely with industry to provide opportunities for developing a stronger low carbon industry in Wales.

1.2 Retrofit strategies

The retrofit strategies to be examined in this research include both existing and emerging low carbon technologies, such as fabric insulation, LED lighting, Transpired Solar Collectors (TSC) (Brown et al. 2014), Mechanical Ventilation Heat Recovery (MVHR), and renewable energy technologies such as photovoltaic panels, etc. The combination of these strategies can be designed through a system based approach to optimise the energy use of the retrofit properties.

Most strategies are to reduce the heating energy

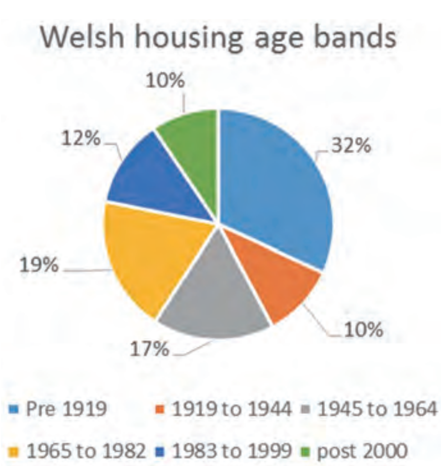

Figure1 Welsh housing age breakdown (VOA 2014)

demand as space heating comprises around 66% of the domestic energy usage in the UK (DECC, 2014b). Among them, fabric insulation could be the most efficient strategies for a previous poorly insulated property. As the space heating demand could be greatly decreased, not only because of the reduced heat loss through the fabric elements, but also due to less heat loss through infiltration as a result of improved air tightness. When the building envelope has been upgraded, it is also a good time to replace the heating system, as it provides an opportunity to downsize the current system, or switch to a more energy-efficient system, considering the great improvement of the efficiencies of gas and oil-fired boiler over the past 30 years, from about 65% to over 90% (Everett 2007). Transpired Solar Collector, also referred as SOLARWALL heater, is a solar air heating system comprised of a pre-finished perforated steel skin installed onto a south-facing wall or roof. Air is heated at the boundary layer of the steel skin which absorbs the solar energy, and will be further heated by the edges of the perforations and the internal side of the steel skin, when passing through the perforations and moving upwards in the cavity between the steel skin and the wall or roof. Its thermal collection efficiency can exceed 70% if designed properly (Brunger et al. 1999). Mechanical Ventilation Heat Recovery is an energy recovery system employing a counter-current heat exchanger between the air inlet and outlet. It can not only reduce energy requirements by offering free heating or cooling energy, but also improve the thermal comfort and air quality indoor by providing fresh air and improved climate control.

Besides the strategies to reduce heating demand, attention has also been paid to decreasing electricity demand and meeting these demands through the application of renewable energy technologies. Most LED light lamps can save over 80% electricity compared to conventional incandescent lamps do (DoE 2014), and could last longer with less maintenance. According to estimation, the current average annual solar resource in the UK is 101W/m^2 (Burnett et al. 2014), or 2.4 kWh/m^2/day. Solar PV is preferred, in comparison to solar thermal, due to the large amount of storage heat loss and distribution heat loss in the solar thermal system. It is also because a place to hold the hot water cylinder is required in the solar thermal system, which is not always feasible for a Wales house where the combi-boiler system without a hot water tank has become a standard system option. While for the case of solar PV, electricity generated from the PV roof can be used onsite either to support the electricity appliances such as LED lighting, or to provide domestic hot water by using an immersion heater in the case of a system boiler with hot water tank, with the surplus power exported to the grid, contributing to a low carbon energy system.

2 Methodology

At an early stage for retrofit design, it is often necessary to examine a range of options quickly. Building simulation can be a very effective way to predict the performance optimisation of the property in relation to its energy reduction, operating cost saving and carbon emission reduction. Figure 2 illustrates the framework for a dynamic modelling-based low carbon retrofit design. The model is required to be built on information gathered from the specific house to ensure the accuracy of the simulation. Information in preparation for the modelling includes climate data, site location and surroundings, dimensions and fabric constructions of the building, design condition indoor, etc. It could be adjusted as the retrofit work goes on when more and more details are being checked and confirmed, contributing to more realistic simulation results. The building performance after retrofit can be monitored to compare with the simulation results. However, it will not be covered in this paper as the current monitoring data is only available for the first two or three months.

At the start of each retrofit, a series of investigations were carried out, meetings were held between stakeholders to discuss solutions for potential obstacles, and how to meet the targets in an effective way. Different groups of strategies

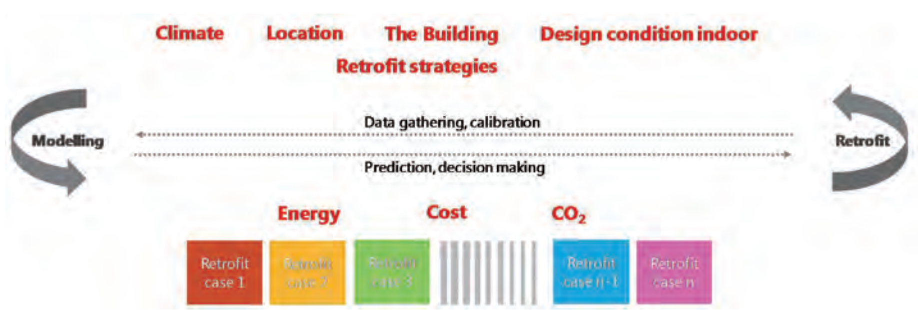

Figure2 Modelling-based low carbon retrofit design framework

were then proposed, such as a fabric approach, a system based approach, or a mix of both depending on the pre-retrofit condition. It's generally accepted that low carbon building design follows a route from firstly reducing internal heat loads, then passive design, using efficient service systems, and integrating renewable energy supply (Jones et al. 2015). Therefore, strategies in this research are proposed based on a fabric first sequence. These strategies included external wall insulation, loft insulation, low-E double glazing, LED lighting, TSC, MVHR, solar PV roof. Additional factors, as a result of the implementation of these strategies have also been considered, including good air tightness due to replacement of high performance fabric, shading mask from external wall insulation, and smaller heating volume due to solid ground and internal wall insulation. Following this, different options were modelled and assessed to explore their impact on the energy consumption, carbon reduction and operating cost savings. The best option for each house was identified and agreed, with consideration to the potential benefits from the performance optimisation, as well as meeting the budget and time requirements.

The software employed in the research included HTB2, VirVil SketchUp (Jones et al. 2013) and Excel. Both HTB2 and VirVil SketchUp were developed at the Welsh School of Architecture, Cardiff University. HTB2 is typical of the more advanced numerical models, using as input data, hourly climate for the location, building materials and construction, spatial attributes, system and occupancy profiles, to calculate the energy required to maintain specified internal thermal conditions (P.T. Lewis, D.K. Alexander 1990). Due to its advantages of flexibility and ease of modification, it is well suited for use in the field of energy efficiency and sustainable design of buildings, which is rapidly evolving. The software has been developed over thirty years, and has undergone a series of extensive testing and validation, including the IEA Annex 1 (Oscar Faber and Partners 1980), IEA task 12 (Lomas 1994) and the IEA BESTEST (J. Neymark et al. 2011). VirVil SketchUp is an extension development of HTB2 for urban scale modelling. By linking SketchUp with HTB2, it can carry out dynamic thermal simulation for multiple buildings in a community or urban scale, with consideration to the overshadowing impacts from the neighbourhood.

The workflow for a whole simulation run is illustrated in Figure 3. VirVil SketchUp was firstly used to generate shading mask for the individual window of the retrofit houses. This data together with other information, including climate, location, building fabric, design condition indoor etc., were then supplied to the energy model, and the thermal simulation was run in HTB2, with results displayed and handled in Excel. This was to calculate the space heating demand and the renewable energy supply, namely the solar PV power. Other energy demands including electricity and domestic hot water were estimated based on information gathered onsite or referring to regulation or database in relation to this. The solar PV power was then used to meet part or all of the electricity demand, or provide domestic hot water, depending on what kind of systems had been linked. The total gas consumption could be calculated by adding together these to supply the remaining domestic hot water and those to meet the space heating demand. In the case of using electricity to supply hot water such as electric shower, this amount of energy should be deducted from the gas consumption, while be added to the electricity consumption. The final electricity consumption would be a sum of all electricity demand deducted by those met by renewable energy supply.

The calculation of carbon emission and cost was based on the operating energy data obtained above. For example, the potential carbon emission could be got by multiplying the individual energy consumption with the related carbon dioxide emission factor (BRE 2014), with the surplus PV power to grid contributing to a negative carbon

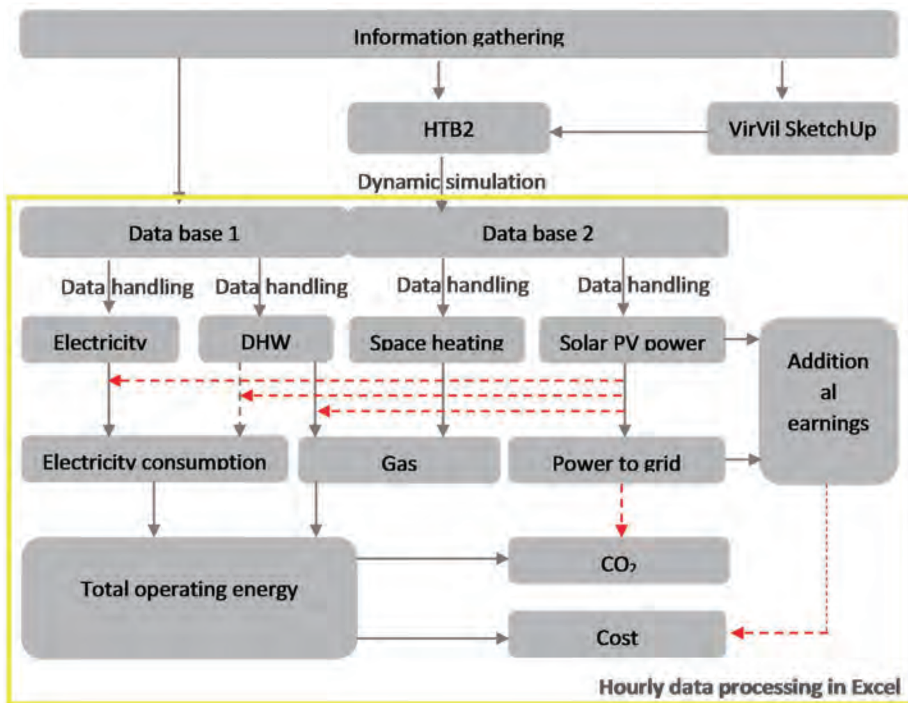

Figure3 workflow for a simulation run

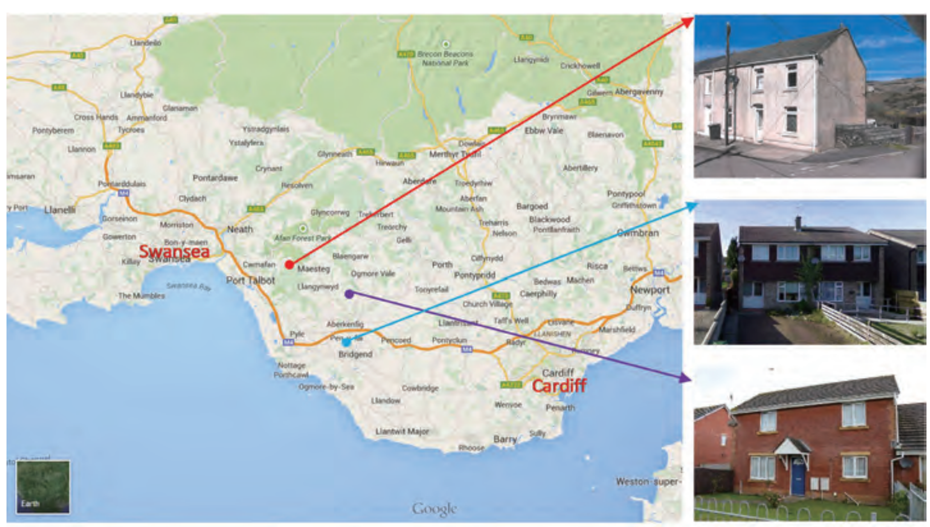

Figure4 locations of the 3 retrofit houses

Table 1 Basic building information of the 3 retrofit properties

Properties	Property 1	Property 2	Property 3
Location	1 Galltcwm Terrace, Byrn, Port Talbot, Neath Port Talbot	8 Cricklewood Close, Bridgend	13 Tyn-Y-Waun Bettws, Bridgend
Type	A pre-1919 solid wall, end terrace, 2 bedrooms, 2-storey, typical Welsh valley house	A 1960s, 3-bedrrom, 2-storey, semi-detached house	A 2000s, 3-bedrrom, 2-storey, semi-detached house
Floor area	$67m^2$	$70m^2$	$86m^2$
Key features before retrofit	• Solid external wall • Cavity wall without insulation (rear extension) • Solid ground floor without insulation • Loft with 250mm insulation • Flat roof without insulation (rear extension) • Single glazing • System boiler	• Cavity wall without insulation (gable) • Retro-filled cavity wall (rear wall and ground floor front wall) • Solid ground floor without insulation • Loft with 100mm insulation • Double glazing • Combi-boiler	• Retro-filled cavity wall • Solid ground floor without insulation • Loft with 150mm insulation • Double glazing • System boiler

Table 2 Typical design condition indoor for the retrofit properties

Space	Heating	Internal gains		
		Occupancy	Lighting	Small power
Sitting room	20˚C, at 7-9, 16-23, weekday; 20˚C, at 7-23, weekend;	17-23, 72W, weekday 8-23, 72W, weekend	17-23 110W, all week	TV: 17-18 135W 20-22 158W all week
Kitchen		7-8 & 18-21 84W weekday; 7-8, 12-13 & 18-21 84W, weekend	7-8 & 18-21 56W weekday; 7-8, 12-13 & 18-21 56W, weekend	Cooker: 7-8, 1190W & 18-19 1700W for weekday; 7-8 & 12-13 1190W, 18-19 1700W for weekend; Fridge: 0-24 60W all week H. water: 0-24 77W all week
Dining		8-9, 140W &18-20 115W weekday; 8-9 & 13-14, 140W &18-20 115W weekend	8-9, 126W &18-20 171W weekday; 8-9 & 13-14, 126W &18-20 171W weekend	
Bedroom 1 (main)		0-8 &23-24, 148W, all week		
Bedroom 2/3 (children)		0-9 &21-24, 38W, all week		
Bathroom		7-8, 100W 17-18, 40W 21-23, 35W all week	7-8, 100W 17-18, 40W 21-23, 35W all week	Hot water: 0-24 77W all week
Note: According to pressure tests before retrofit, the infiltration rate of the individual property is 0.73 for first retrofit house, 0.54 for the second one, 0.33 for the third one. (Allen E. and Pinney A., 1990)				

emission. While the operating energy costs were calculated directly with the fuel prices quoted online. Additional income from the installation of solar PV has also been considered following the UK Government's Feed-in Tariffs scheme (FITs), a government designed programme to promote the uptake of renewable and low-carbon electricity generation technologies in small scale. That means a payment for each unit of electricity generated, no matter whether it's used by the household or exported to the grid, and for any unit of surplus electricity exported to the grid. For a domestic system which is unlikely above 30kWp, the installation of an expensive smart meter is not required, and it is normally estimated that 50% of the electricity generated is exported to the grid.

3 Simulation conditions

The three retrofit properties are located between Cardiff and Swansea, in south Wales, UK (See Figure 4). Before simulations were carried out, the following information had been collected,

(1) Weather data. HTB2 only accepts a meteorological file, which can be converted from the most common weather data format EPW file by using Weather file Convertor, a sub-software of HTB2. The original EPW files for the three retrofit houses were produced by meteonorm V7.1.1.122.

(2) Building model. The building model comprises two parts, the dimensions of the house and the building fabric. Table 1 summarised the basic building information for the 3 retrofit properties, which had been gathered through field study by expertise from the building industry.

(3) Design condition indoor. Data regarding building services, including heating, ventilation, internal gains from people, lighting and other appliances. Information in relation to this has either been collected from investigations such as air tightness tests, or referred to typical scenarios (see table 2).

(4) Retrofit strategies. Please see the next section for details regarding the specific retrofit strategies proposed for the individual house, and the related simulation cases.

(5) Carbon dioxide emission factor (see table 3).

(6) Fuel prices and Feed-in Tariffs (see table 4).

4 Case study: performance optimization prediction

4.1 Retrofit house 1

Based on a fabric first sequence, the following retrofit strategies were proposed for the house,

Table 3 Carbon dioxide emission factor and Primary energy factor

Fuel	Primary energy factor	Emissions (Kg CO_2/ kWh)
Gas (mains gas)	1.22	0.216
Electricity	3.07	0.519
Quoted from SAP 2012: table 12 (BRE, 2014)		

Table 4 Fuel prices and Feed-in Tariffs

Category	Tariff (p/kWh)
Gas	5.13
Electricity	16.00
Generation tariff for solar PV	14.38
Export tariff for solar PV	4.77
Quoted from: c. British Gas: http://www.britishgas.co.uk/ , 2014; d. Feed-in Tariff Payment Rate Table for Photovoltaic Eligible Installations for FIT: 1st Apr. 2014-31st Dec. 2014 (Ofgem, 2014).	

Table 5 simulation cases for retrofit house 1

Cases	Retrofit strategies
1	Base case (before retrofit)
2	a) b) c)
3	a) b) c) d)
4	a) b) c) d) e)
5	a) b) c) d) e) f)
6	a) b) c) d) e) f) g)

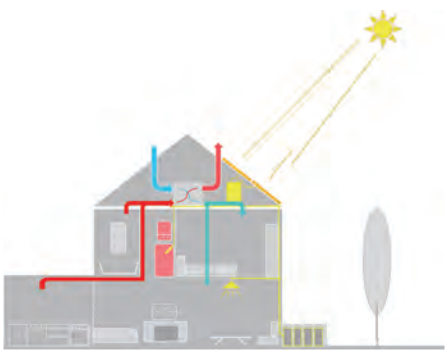

Figure5 Schematic of the proposed system for the 1st retrofit house

with consideration to its pre-retrofit conditions (see table 1).

a) External wall insulation (100mm EPS-60mm below DPC)
b) Low-E double glazing
c) Loft insulation (300mm) & flat roof insulation (50mm, rear extension)
d) LED lighting main circuit
e) MVHR – Energisaver 280 whole house solution
f) PV roof (2.5 kWp, efficiency 14.4%) + lead acid battery storage (4.8 kWh, DoD 50%) + inverter for lighting circuit
g) Energy efficient system boiler (90% efficiency) + hot water cylinder with immersun (an immersion heater)

Figure 5 shows the proposed service systems, with the PV roof supplying power for LED lighting and water heating in the hot water tank. Before work started onsite, simulations were carried out to understand the efficiencies of the retrofit strategies (see table 5). It ranged from a fabric solution to a mix solution to show the possible staged demonstrating benefits in the retrofit process.

According to the simulation result (Figure 6, 7), it is shown that,

(1) The fabric insulation could achieve a 69.2% reduction of gas demand, a 48% reduction of carbon emissions, a 43% operating energy cost saving;

(2) The installation of the LED lighting could reduce electricity demand by 18.8%, but could also increase heating demand by 1.9% due to less heat gain from the LED lamps compared with the incandescent lamps, resulting in an overall 5% reduction of carbon emissions, a 6% cost saving;

(3) The application of MVHR could contribute to a 2% reduction of heating demand, but a 1% increase of carbon emissions and no cost saving,

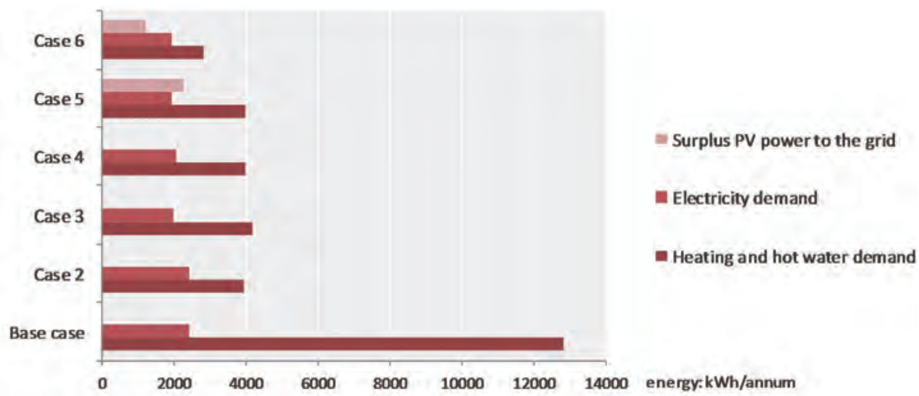

Figure6 Retrofit house 1: a comparison of the energy performance of different cases

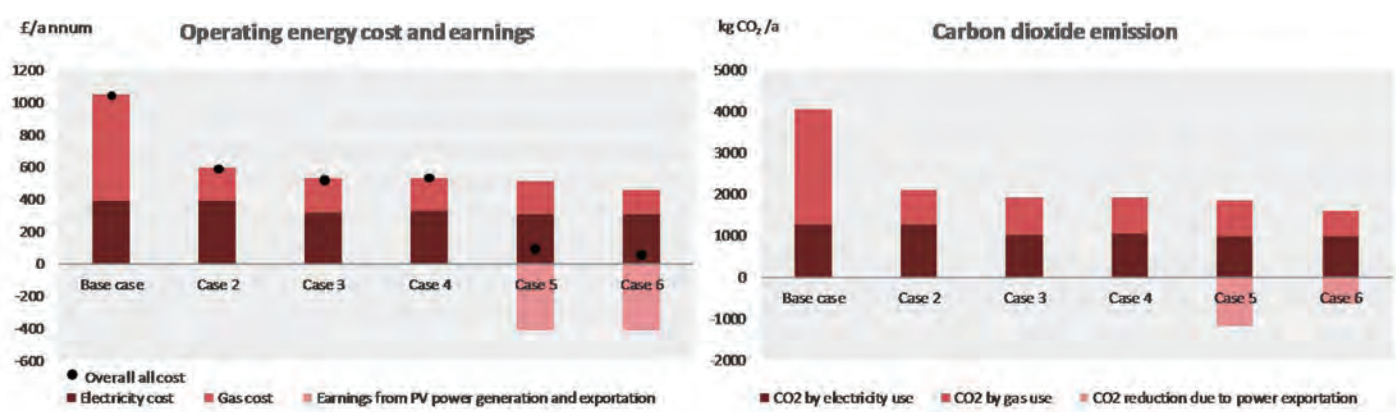

Figure7 Retrofit house 1: a comparison of the operating energy cost and earnings of different cases (left); a comparison of the carbon dioxide emission of different cases (right).

as it also decreases the electricity saving by 4%, due to the additional fan power;

(4) The adding of solar PV & battery to supply LED lighting could only reduce electricity demand by 5%, with more than 90% power generated by PV exported to the grid, contributing to an overall 31% reduction of net carbon emissions and a 40% cost saving considering both operating energy reduction and solar PV power generation and exportation;

(5) While if a hot water cylinder with immersun was integrated in the system, 44% of PV power could be consumed on site to supply up to 90% domestic hot water, which contributes to another 6% cost saving, a 5% reduction of carbon emissions from operating energy consumption, but a 7% increase of net carbon emission due to electricity losses in the AC/DC power conversion processes, and battery charging and discharging processes.

As SOLCER encourages onsite consumption of renewable energy as much as possible, case 6 with less electricity exportation than case 5 was selected as the best case.

4.2 Retrofit house 2

The 2nd retrofit house was found to be partly insulated at the rear wall and the ground floor front wall, and previously supplied with a combi boiler to meet the space heating and hot water demands (see table 1). The following retrofit strategies were proposed accordingly.

a) Bonded bead cavity wall insulation (50mm, gable)
b) Insulated external render (50mm)
c) Kingspan Optimi-R external wall insulation (50mm, the first floor front wall)
d) Loft insulation (300mm)
e) MVHR – Energisaver 280 whole house solution
f) LED lighting throughout
g) PV roof (3.0 kWp, efficiency 14.4%) +lead acid battery storage (4.8kWh, DoD 50%)

As for retrofit house 1, a mixed approach was recommended, but with the PV roof supplying the lighting circuit and a small fridge (see Figure 8), as there is no space to hold a hot water tank. It was estimated that a whole application of the proposed strategies would go beyond budget, therefore some strategies have to be removed. Simulations were carried out in regards to this to assess and compare the performance optimisation of different options. See table 6 for a summary of the cases.

According to the simulation results (see figure 9, 10), the most low carbon option is case 4 with all proposed strategies except MVHR, which could contribute to a 36% reduction of heating demand, a 23% reduction of electricity demand, a 88% reduction of net carbon emission and a 110% cost saving (there is a cost gain to the occupiers from electricity generation and exporting electricity to the grid). While it's obvious that potential benefits brought by case 2, 3 and 6 are very close to that of case 4, therefore they should be taken into account when the final decision is reached. Case 5 without solar PV and battery could be the most economical one, but was the least low carbon option as renewable energy supply was not integrated in the system.

4.3 Retrofit house 3

The 3rd retrofit house was built after 2000 with

Table 6 simulation cases for retrofit house 2

Cases	Retrofit strategies
1	Base case (before retrofit)
2	a) c) d) f) g)
3	a) c) d) e) f) g)
4	a) b) c) d) f) g)
5	a) b) c) d) e) f)
6	a) b) c) d) e) f) g)

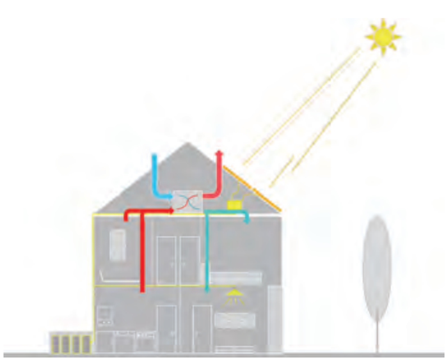

Figure8 Schematic of the proposed system for the 2nd retrofit house

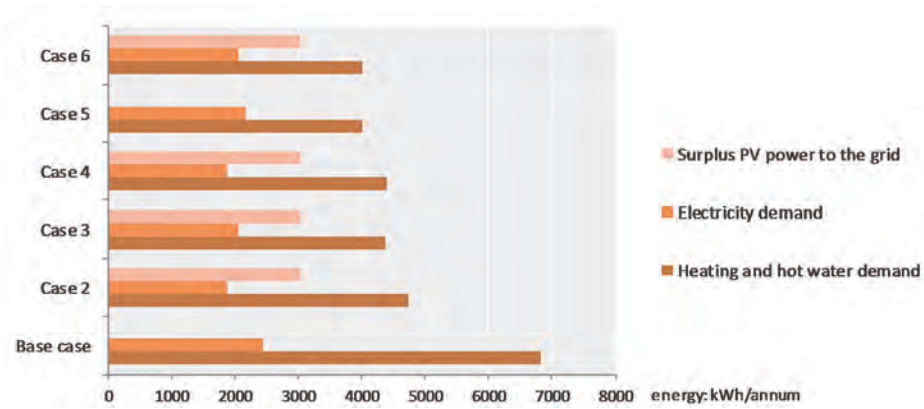

Figure9 Retrofit house 2: a comparison of the energy performance of different cases

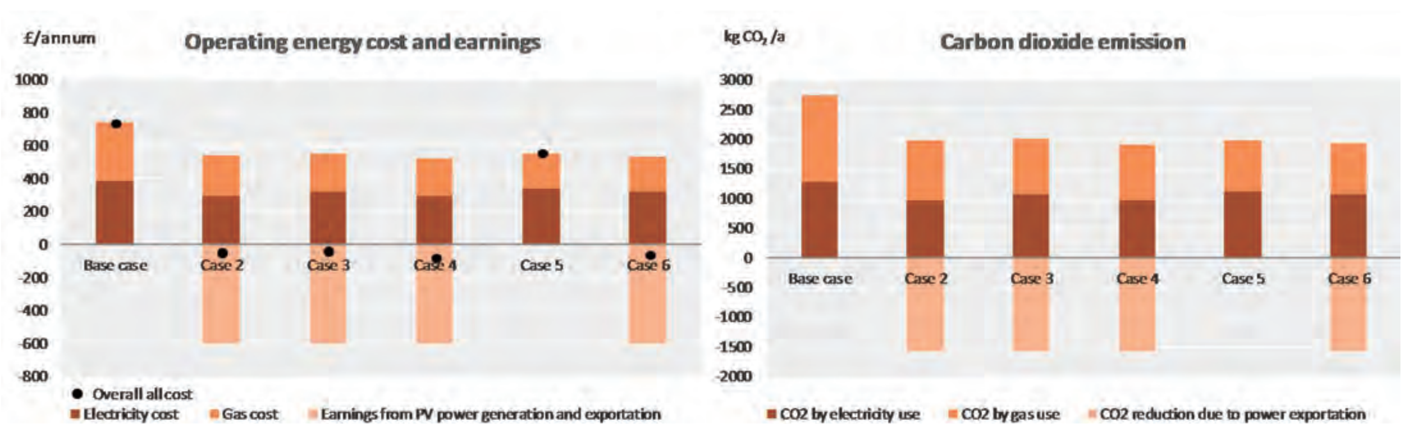

Figure10 Retrofit house 2: a comparison of the operating energy cost and earnings of different cases (left); a comparison of the carbon dioxide emission of different cases (right).

good fabric insulation and a relatively new system boiler (See table 1). It was preliminarily designed with the following retrofit strategies a) – d), mainly a system approach with the PV roof supplying power for all electricity circuits, including the immersion heater in the hot water cylinder. Additional strategies e)-g) were proposed for further improvement if within budget. Figure 11 shows how the proposed service systems work in the retrofit house.

a) Loft insulation (300mm)
b) LED lighting throughout
c) Roof integrated PV array (5 kWp, efficiency 14.4%) + extensive lead acid battery storage (DoD 50%, supplying the whole house)
d) Energy-efficient boiler (90% efficiency) + hot water tank with immersun
e) External insulation rendering (50mm)
f) MVHR– Energisaver 280 whole house solution
g) 4.4m2 Transpired Solar Collector

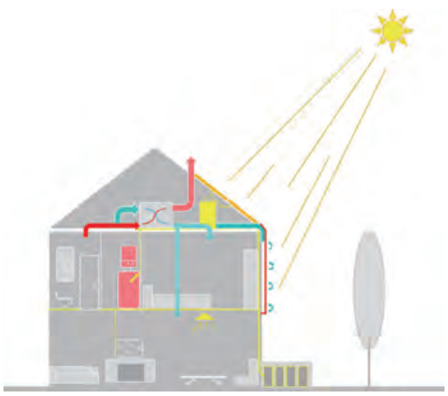
Figure11 Schematic of the proposed system for the 3rd retrofit house

Simulations were carried out to assess the potential staged benefits through the implementation of the retrofit strategies, and also to compare the performance optimization of the preliminary strategies set and that combined with additional strategies.

According to the simulation results (12-13), it could be summarized as below,

Table 7 simulation cases for retrofit house 3

Cases	Retrofit strategies
1	Base case (before retrofit)
2	a)
3	a) b)
4	a) b) c) d)
5	a) b) c) d) e)
6	a) b) c) d) f)
7	a) b) c) d) e) f)
8	a) b) c) d) e) f) g)

(1) For the preliminary strategies set (case 4), a reduction of 24% could be achieved for Gas demand, while 83% reduction for electricity demand; besides, around 1448kWh excessive power could be sold to the grid. These could contribute to a 58% reduction of carbon emission from operating energy consumption, a 93% reduction of net carbon emissions, and a 203% cost saving considering both from operating energy reduction and the PV power generation and exportation.

(2) Combined with additional strategies (case 8), a reduction of 46% could be achieved for heating demand, while 78% for electricity demand reduction; besides, around 1330kWh excessive power could be sold to the grid. These could lead to a 64% reduction of carbon emission from operating energy consumption, a 96% reduction of net carbon emissions, and a 207% cost saving considering both from operating energy reduction and the PV power generation and exportation.

(3) Among all, the most energy-efficient strategies for this property could be LED lighting, the PV roof and batteries, energy-efficient boiler and hot water tank. For the MVHR and TSC systems, they could contribute to a 10-15% reduction of gas demand, but also a 5% increase of electricity demand, due to the added fan power for the MVHR system.

It is obvious that benefits achieved through applying the preliminary strategies set is quite close to that of the case combined with additional strategies. Therefore both options should be considered when making the final decision.

Besides, the performance of individual component has also been examined. The calculated peak power output from PV is 4.6kW, assuming an efficiency of 14.4%, with all roof area ($30m^2$) covered

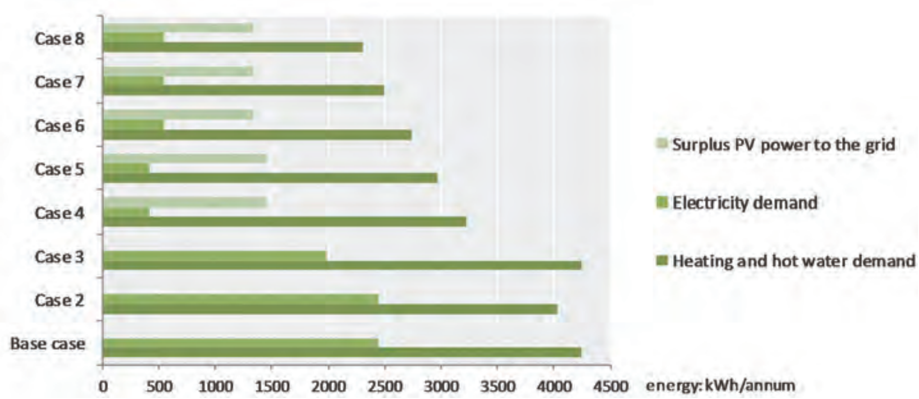

Figure12 Retrofit house 3: a comparison of the energy performance of different cases

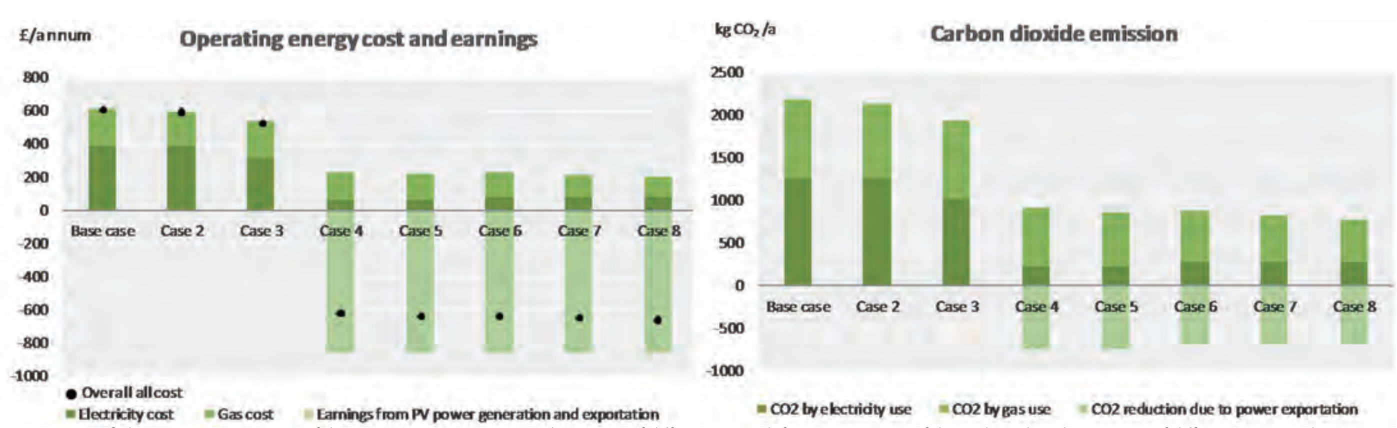

Figure13 Retrofit house 3: a comparison of the operating energy cost and earnings of different cases (left); a comparison of the carbon dioxide emission of different cases (right).

by PV. For cases with battery storage (assuming 50% for DoD and 60% for charging and discharging efficiencies), the battery capacity was selected as 8kWh with regards to its impact on the total power reduction, and the relevant cost (referring to that of the 1st retrofit properties). Figure 14 shows the predicted relationship between the air temperature rise through the TSC and the related solar radiation on the TSC, which is very close to the reference data (Conserval Engineering Inc. 2003).

5 Discussion and conclusion

Based on the simulation results, further discussion was carried out between stakeholders. The final decision was reached (see table 8), with consideration to other factors including time and budget requirements. It can be seen that,

(1) All strategies proposed for the 1st retrofit property were implemented.

(2) For the 2nd retrofit house, case 3 was selected, as no insulated external render can be sourced from Wales. The MVHR, although predicted to be not so energy-efficient, was installed to improve the air quality and thermal comfort indoor. Compared with the 1st retrofit, this house was finally installed with a larger battery storage, with consideration to a bigger PV area, and also as it was an iterative learning process with each retrofit when dealing with the battery capacity and capabilities.

(3) For the 3rd retrofit house, additional strategies including TSC, MVHR and insulated render were not implemented due to budget control and tight retrofit schedule. A battery storage, over twice of the size predicted, was installed to test the performance of a system supported by a relatively large battery storage. As above, a step was taken forward with each retrofit when selecting the battery capacity.

Based on information confirmed in making final decision and post-retrofit investigation (such as air tightness tests), simulations were carried out in regards to the actual improvements of the retrofit properties. Figure 15 and table 9 compared and summarized the performance optimization benefits predicted for the final retrofit cases. Through a system approach with solar PV supplying power for the whole house, house 3 achieved the biggest electricity reduction, cost savings, and carbon reduction. While the retrofit of house 1 reduced the most gas demand as the other two houses were relatively new and already had reasonable thermal

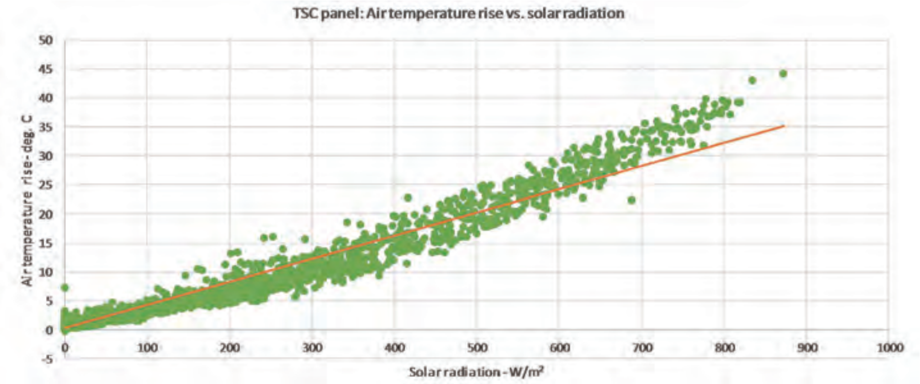

Figure14 TSC panel: Air temperature rise vs. solar radiation

Table 8 A summary of the implemented retrofit strategies

Properties	Property 1	Property 2	Property 3
Retrofit strategies implemented	A mix approach: • External wall insulation (100mm EPS-60mm below DPC) • Low-E double glazing • Loft insulation (300mm) & flat roof insulation (50mm) • MVHR – Energisaver 280 whole house solution • LED lighting main circuit • PV roof (2.5 kWp) +lead acid battery storage (4.8kWh)) + inverter for lighting circuit • System boiler + hot water cylinder with immersun	A mix approach: • Bonded bead cavity wall insulation • 50mm Phenolic EWI (first floor front wall) • Loft insulation (300mm) • MVHR – Energisaver 280 whole house solution • LED lighting throughout • PV roof (2.7 kWp) +lead acid battery storage (8.5kWh)	A whole systems approach: • Loft insulation (300mm) • LED lighting throughout • 4.5 kWp Roof Integrated PV Array • 18kWh Extensive lead acid battery storage; • New Boiler with Hot Water Tank (+ Immersun type device) to supply annual hot water and winter heating.
On-site renewable energy system	The PV roof supplies electricity for LED lighting and water heating in the hot water tank.	The PV roof supplies the lighting circuit and a small fridge.	The PV roof supplies electricity for all electricity circuits, including heating water in the hot water tank.

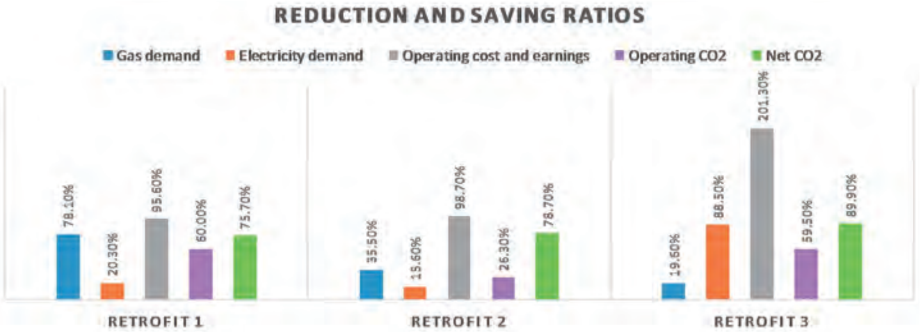

Figure15 A comparison of the actual performance improvement predicted for the retrofit properties

Table 9 the actual cost benefits predicted for the retrofit properties (£/year)

Properties	Annual operating cost saving	Annual earnings from electricity generation and export	Total annual savings
1	594	410	1004
2	185	546	731
3	389	837	1226

insulation levels.

Above all, a lot of effort had been taken to tailor the best practice approach to meet requirements of different retrofit properties. The following conclusion can be made,

(1) A fabric approach could greatly optimize the energy performance of a previous poor insulated house.

(2) For a conventional systems based approach such as the installation of the PV panel (the 2nd retrofit house), most power generated by photovoltaic panels would be exported to the grid. While if with a hot water cylinder and an immersion heater powered by the photovoltaic panels was installed (the 1st retrofit house), around 1/3 of this photovoltaic power could be used to provide domestic hot water. Or if more electricity circuits were integrated with the PV system (the 3rd retrofit house), the total power demand from the grid could be reduced by around 90%, and net export to the grid would be only 1/4 of the total power generated.

(3) When designed properly, a systems based approach with renewable energy supply could reduce carbon emission from operating energy by 60%, net carbon emission (combined with negative carbon due to power exportation) by over 90%, and save total cost by more than 200% considering both operating cost reduction and earnings for renewable energy generation and export.

6 Future work

The simulation results will be compared with monitoring data at the next stage when annual data is available.

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