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Optimization of dwelling design under current and future climates using parametric simulations in EnergyPlus

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Abstract

Designers of low energy dwellings face many challenges in making best use of space, and providing day lit and pleasant spaces, while minimising heat loss and overall carbon emissions to meet various environmental and legislative targets. These also have to be achieved within financial, spatial and planning constraints. In other words, the design exercise is a multi-criteria optimization exercise. Usually this is done using experience through iterative design development, assisted by various software tools ranging from relatively simple models such as the Standard Assessment Procedure (SAP), to detailed thermal simulation. This paper describes the use of parametric simulations using EnergyPlus on a computer cluster to arrive at optimal solutions, for both current and future climates. The tool is applied to some modern house designs proposed for developments in the UK.

Keywords Simulation, optimisation, energy, house

1.0 Introduction

There are demanding targets for carbon emission reductions, greater energy security and improved energy efficiency. As unit fuel prices rise while economic growth remains elusive, householders are perhaps for the first time taking an interest in the energy running costs of new homes [1]. In parallel, there is a lot of pressure and increasingly tough mandatory requirements for new homes to be more efficient – for example the 2010 Building Regulations Part L in England and Wales introduced a (calculated) 25% improvement on 2006 carbon emissions standards for new buildings. By 2016, it is intended that all new homes will be ‘zero carbon’ [2].

Until insulation and air tightness standards improved in the 1990s, most of the energy use in UK homes was for space heating, so improvements were focussed on reducing fabric heat loss through improved insulation and reducing infiltration. For homes built to the England and Wales 2010 Part L regulations (or devolved equivalents in Scotland and Northern Ireland), space heating demands are much reduced (though still significant), and energy for hot water, lighting, cooking and electrical appliances make up a much greater proportion of total energy compared to older homes. Higher standards such as the German Passivhaus reduce space heating demand even further [3] (limited to 15 kWh/m2), to the point where homes may not need any heating system.

Compliance calculation methods such as the Standard Assessment Procedure (SAP) [4], originated at a time of much lower insulation standards, are not really designed to cope with very low heat loss dwellings. Also, such formulaic approaches often fail to recognise ‘good design’ – for example SAP does not take account of daylight in reducing electrical demand for lighting. Finally, different standards have different targets; Passivhaus concentrates on space heating and overall primary energy, while others have overall carbon targets.

Thus the designer faces various challenges and trade-offs in balancing targets for energy, carbon and comfort:

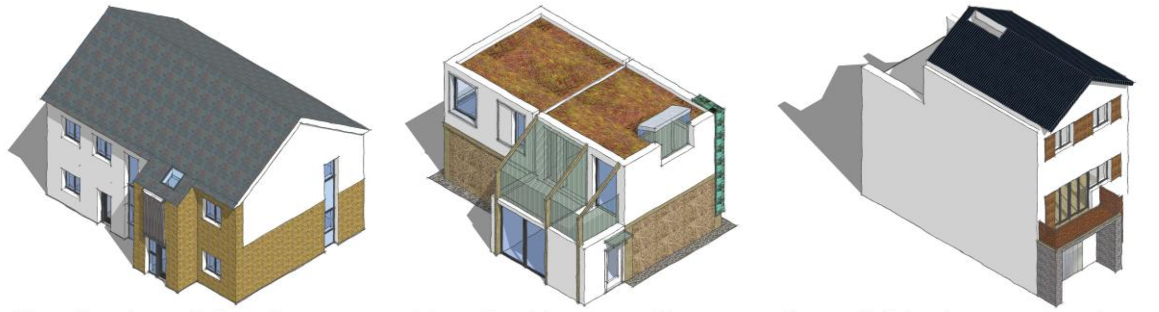
- reducing space heating demand
- reducing lighting demand
- avoiding overheating (in current and a future, probably warmer climate)
- choosing energy systems and fuels
- building within a budget

Often these are in conflict; larger south facing windows will reduce heating demand but are likely to increase overheating [5]; thermal mass usually slightly increases heating use, but can reduce overheating and improve comfort – and most importantly, most low energy measures will cost more.

Building simulation is very useful for analysing the effects of multiple interacting factors, and – if set up carefully – are likely to be more reliable than simplified methods such as SAP. However, if done as a series of individual runs employing user judgement to alter input parameters, the process is time consuming and unlikely to lead to an optimal solution. Recent developments in computing power have lead to building simulation being combined with genetic algorithms to find optimal solutions [6], typically on two criteria. This paper describes the use of such an approach for five house designs, optimising on overall carbon emissions and overheating hours.

2.0 Simulation models of modern houses

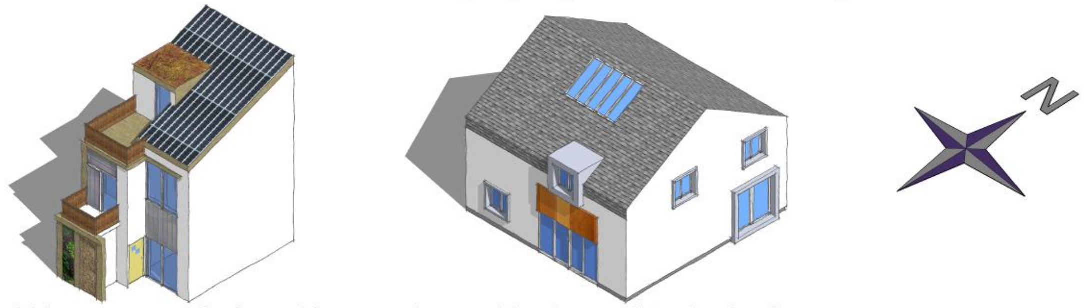
Five house types were simulated, as shown in Figure 1. These are sketch designs for low energy homes, developed by Studio Urban Area LLP[1]. An orientation of zero in the simulations (north) would equate to the buildings shown facing to the top right hand corner of the image, as indicated by the arrow.



Housing Association 3 bedroom semi detached

Mews/end terrace with integral garage: 2 bedroom

Large 3/4 bedroom urban terrace; designed for east-west orientation



Urban terrace, designed for south facing, 3/4 bedroom.

Large 4 bedroom detached unit; design supports external expansion

Figure 1 - The five house types modelled; images from Google Sketchup models

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[1] http://www.urbanarea.co.uk/

The houses were simulated with the following thermal properties and variations allowed.

2.1 Construction elements

While roof and floor elements were specified to fulfil the latest building regulations and were kept unchanged during simulation process, the exterior wall construction and glazing type were selected as a parameter allowed to be varied. Three types of the exterior wall construction were included in the analysis. Type one is composed of four layers: exterior brick layer, insulation layer (XPS Extruded Polystyrene), concrete block layer and gypsum plastering layer. Exterior wall type two has five layers: exterior brick layer, air gap, plywood sheathing layer, insulation layer (XPS Extruded Polystyrene with timber studding) and gypsum plastering layer. Exterior wall type three differs from the exterior wall type two only in the material used as an exterior layer. Namely, in the type 3 the brickwork has been replaced with the wood. Materials used in the exterior wall construction, as well as their thicknesses, can be seen in Table 1.

Exterior Wall Construction	Type 1	Type 2	Type 3
Outside layer	105mm Brickwork	105mm Brickwork	13mm Wood
Layer 2	Insulation	50mm Air Gap	50mm Air Gap
Layer 3	100mm Concrete Block	19mm Plywood Sheathing	19mm Plywood Sheathing
Layer 4		Insulation	Insulation
Inside Layer	13mm Gypsum Plastering	13mm Gypsum Plastering	13mm Gypsum Plastering

Table 1 - The three types of an exterior wall used in house models

Insulation layer in the exterior walls type two and type three is made of XPS Extruded Polystyrene and timber studding, which means that material properties (such as density, conductivity and specific heat) has to be adjusted to reflect the presence of a timber in the insulation layer. The previous building regulations specified a nominal timber fraction of 6.3%. Bell and Overend [7] reported that this fraction can be much higher; even above 30%. CIBSE Guide A 2006 [8] indicates 3 values to be used: 20% for narrow walls with doors, windows, bay windows; 15% for typical wall with windows and doors; and 10% for walls without windows and doors.

Combined property (p) of such a layer was calculated as follows:

$$p(\text{combined}) = t * p\,(\text{wood}) + (1-t) * p\,(\text{insulation}) \qquad (1)$$

where p is a material thermo-physical property (density, conductivity or specific heat), and t is a timber fraction. It was found that a timber fraction of 15% required exceptionally thick insulation layers to achieve U values around 0.12 W/m^{2}K.

Therefore a timber fraction of 10% was used for determining the insulation layer combined properties, on the basis that the frame would have to be designed with less timber, or some sort of thermal breaks, for high performance walls.

The insulation layer thickness in the exterior wall constructions was varied from 50mm to 350mm in 50mm increments. The effect of this on exterior wall U-values is presented in Table 2.

Wall type	Insulation layer thickness [mm]						
	50	100	150	200	250	300	350
Type 1	0.55	0.3	0.21	0.16	0.13	0.11	0.09
Type 2	0.65	0.38	0.27	0.2	0.17	0.14	0.12
Type 3	0.66	0.38	0.27	0.2	0.17	0.14	0.12

Table 2 - The exterior wall U-values [W/m2K] as a function of insulation thickness

In addition to the exterior wall types and the insulation layer thickness, eight glazing types were specified as a design option: two double-glazed units and six triple-glazed units. Double-glazed units are made from 4mm outer clear glass pane, 4mm inner Low-emissivity glass pane and 12mm cavity between panes. They differ in the type of gas used to fill the cavity; air and argon. Four triple-glazed units are made of 4mm glass panes and 12mm cavities filled either with air or with argon. Two of them have all glass panes made of clear glass, while other two have two interior Low-e glass panes. The last two triple-glazed units used in the study are made of 6mm glass panes and 13mm cavities filled with air. Exterior pane is made of clear glass in both units, while interior panes have improved characteristics in order to reduce solar heat gains. Unfortunately, this type of glass panes lower light transmittance too. Basic characteristics of glazing units selected for the analysis such as U-value, solar heat gain coefficient (SHGC) and light transmittance (LT) are presented in Table 3.

Glazing type	U-value [W/m^{2}K]	SHGC	LT
1. Double 4-12-4 Low-e Air	1.95	0.63	0.76
2. Double 4-12-4 Low-e Argon	1.84	0.63	0.76
3. Triple 4-12-4-12-4 Clear Air	1.78	0.66	0.72
4. Triple 4-12-4-12-4 Clear Argon	1.63	0.66	0.72
5. Triple 4-12-4-12-4 Low-e Air	1.05	0.49	0.65
6. Triple 4-12-4-12-4 Low-e Argon	0.9	0.49	0.65
7. Triple 6-13-6-13-6 Low-e(55) Air	1.14	0.31	0.46
8. Triple 6-13-6-13-6 Low-e(66) Air	1.15	0.36	0.54

Table 3 - Glazing type properties

Finally, the orientation as a simulation parameter was also included in the analysis by rotating the houses at 45 degree intervals (zero being north for the facades shown in Figure 1), giving a total of eight orientations.

2.2 Infiltration and ventilation

Proposed houses were designed as low-energy homes, assuming to be very tight, which is the reason why the infiltration level used in the analysis was set to 0.15 air changes per hour (ACH). Fresh air requirements were obtained by allowing 10 l/s per person of outdoor air to be distributed to the occupied zones within the house. In order to reduce/prevent overheating during warm periods, additional 6 ACH were introduced to the lounge areas and bedroom zones (during occupied period) whenever the outdoor temperature rises over 22°C. This represents the open windows, which is highly possible to happen during warm periods.

2.3 Internal gains and occupancy

Occupant's density, as well as occupancy patterns, equipment power and use schedules were adopted for each individual zone (bedrooms, lounges, kitchens, dining areas, bathrooms, and corridors) based on the national calculation methodology (NCM) recommendations.

2.4 Lighting control

Although it is not common to have daylight control in domestic buildings, such control has been applied to the lounge spaces and the bedrooms to reproduce highly possible scenario of switching lights off (completely or partially) when there is enough daylight. Applied daylight control works in the following way. The interior daylighting illuminance level was calculated at specific reference point and then compared with illuminance target value (400 lux in this case). Artificial lighting was reduced whenever it is possible to benefit from daylight while still achieving the desired target. Lights were dimmed continuously and linearly from maximum to minimum electric power (light output) as the daylight illuminance were increased. Once the minimum point was reached, the lights were turned off completely.

2.5 Heating control

The houses heating demand was calculated assuming that the ideal system is installed which can provide enough energy to secure desired thermal comfort conditions. Thermal comfort conditions were represented through the air dry-bulb temperature setpoint which was set to 21°C in the lounge zones and to 18°C in all other zones during occupied period. During unoccupied period the temperature setpoint was set to 12°C to prevent overcooling and to avoid condensation/frost damage.

3.0 Optimisation by parametric simulations

The method used in this study is full parametric search for the global optimal design of each house type in various climate conditions. This is in fact done by creating a large parametric project encompassing all design scenarios and options, including climate conditions, house types, orientation, wall constructions, insulation level, and glazing types. Optimal designs in terms of operational carbon emission and overheating risks are identified by post-processing the simulation results. Parametric simulations are carried out with EnergyPlus and jEPlus [9].

3.1 Climate conditions

Prepared models were simulated by using current and future climate weather files, in particular Heathrow weather files. Three weather files were obtained from Prometheus project [10]. These were:

- current climate 1961-1990 [current]
- 2050s medium (A1B emissions scenario) [2050 M]
- 2050s high (A1F1 emissions scenario) [2050 H]

3.2 Optimisation objectives

The two design objectives used in this study were annual CO2 emissions (normalised per net floor area) and total number of overheating hours during occupied periods in lounge zones and bedrooms. The annual CO2 emissions were calculated by taking into account both heating energy and electricity consumption. It was assumed that the heating demand is covered by a gas fired boiler with an overall heating efficiency of 0.85 and that the electricity for lighting and equipment is supplied from the grid. The following greenhouse gas conversion factors were used:

for the natural gas – 0.185 kg CO2/kWh and for the grid electricity – 0.537 kg CO2/kwh. Overheating hours were calculated for the occupied periods (when people are present) by counting number of hours when the zone temperature is greater than 25°C in any one or more zones (only living rooms and bedrooms were taken into consideration, kitchens were excluded because these often overheat due to internal cooking gains). So one hour with three zones occupied and overheating would count as 3 overheating hours.

3.3 Parametric simulation project

Combining three weather years, five houses, three exterior wall construction types, seven insulation levels, eight glazing types and eight orientations gives 20,160 possible scenarios as presented in the parameter tree in Figure 2. The total number of designs for each house type in each climate condition is 1,344. Simulations were carried out on a DMU Cluster with 200 available cores, and the total simulation time was around 2.5 hours.

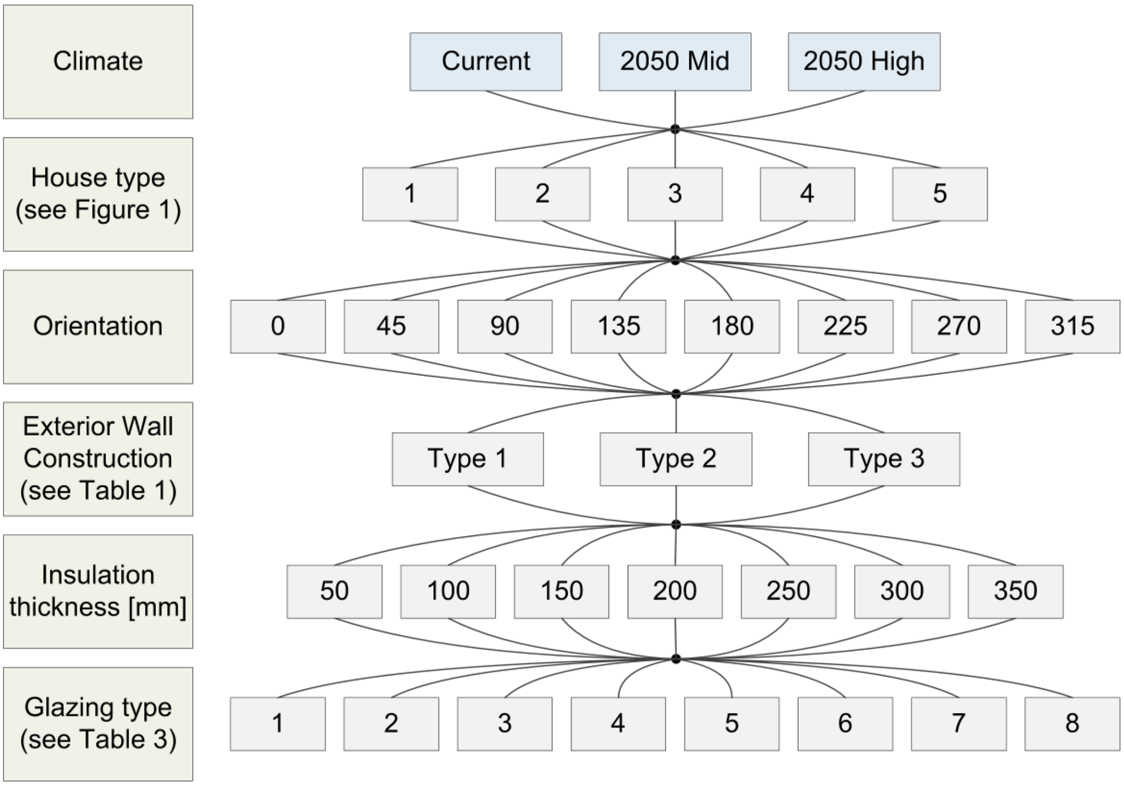

Figure 2 - Parameter tree

4.0 Results

Figure 3 shows all the results in terms of carbon dioxide emissions on the y-axis plotted against overheating hours on the x-axis. Blue circles or 'points' represent non-optimal solutions, green circles 'optimal' solutions (in terms of a combination of CO2 and overheating) along the 'Pareto Front' – this is the 'edge' of the point cloud nearest to the x/y axes. For optimal solutions, there is no solution which has a lower overheating and a lower CO2 level. The designer could choose which of the optimal set to use, depending on where the balance between overheating and CO2 lay.

Several things are worth noting. The CO2 emissions are lower in the 2050s due to warmer winters. Differences between current climate and 2050s climate are greater than between the medium and high scenarios 2050s climate, as might be expected, with a lot more overheating in the 2050s. For the same reasons, the main variation of optimal solutions for current climate is in CO2 (along the y-axis), but in overheating for the 2050s climates (along the x-axis). This suggests the greater challenge for design lies in overheating, not heat loss, for future climate. The high level of overheating in all cases for the 2050s is also striking; whereas in the current climate no optimal designs have more than 500 hours overheating, in both the 2050s climates almost all the solutions, for all house types, have more hours than this. The pattern for each house type is different, though 1, 2 and 5 are quite similar. Type 3 shows much less variation in both dimensions than the other types; this may be because it is a terrace with less glazing than other types and hence is less influenced by the outside climate. There is distinct 'banding' of points for type 4; this is due to sets of results with one parameter constant, and is present in other types but less obvious because of the smaller spread of results.

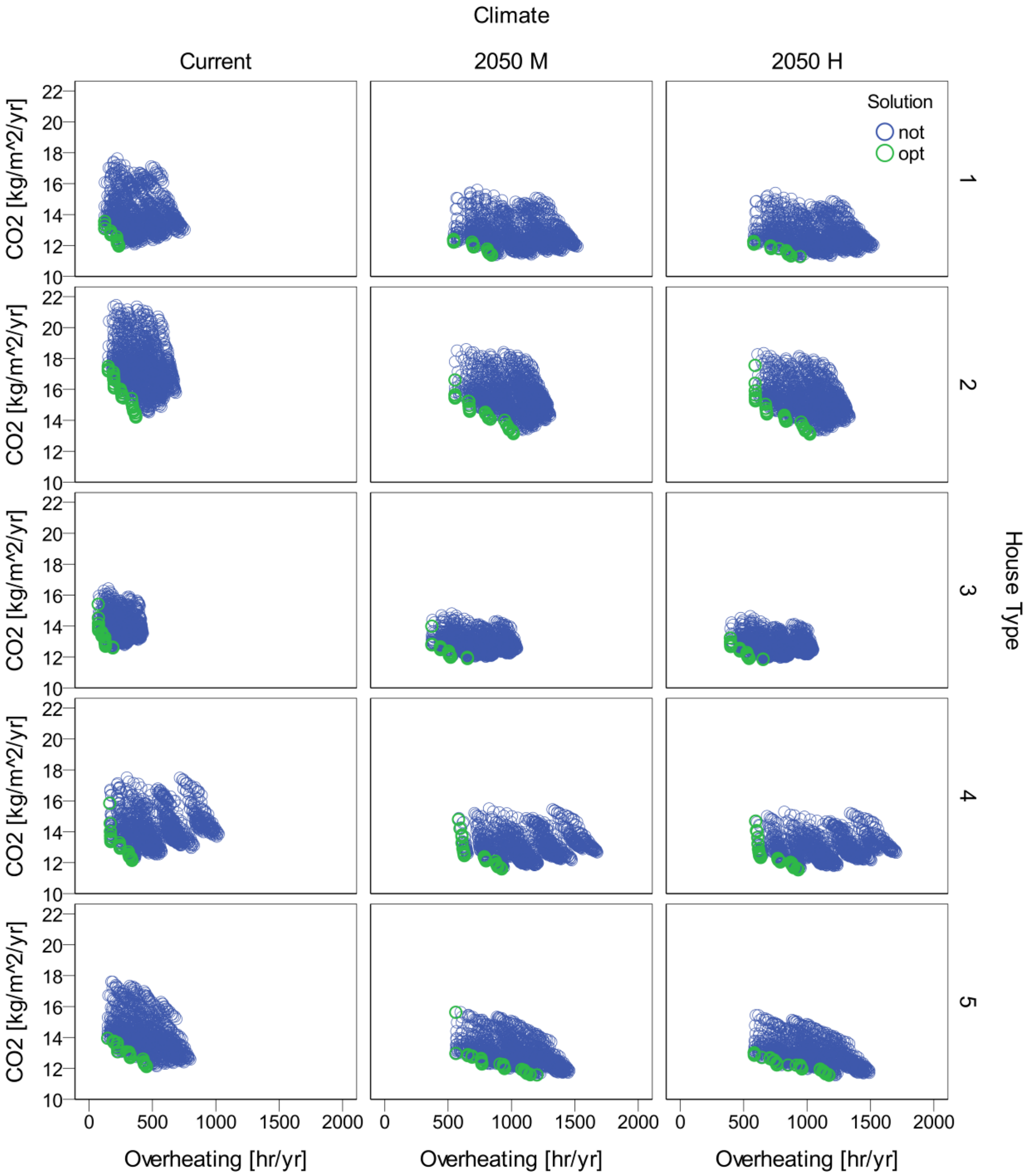

Figure 3 - Plots of overheating and carbon dioxide results for all runs, by house type (rows) and climate year (columns); each circle represents one run, green are 'optimal'

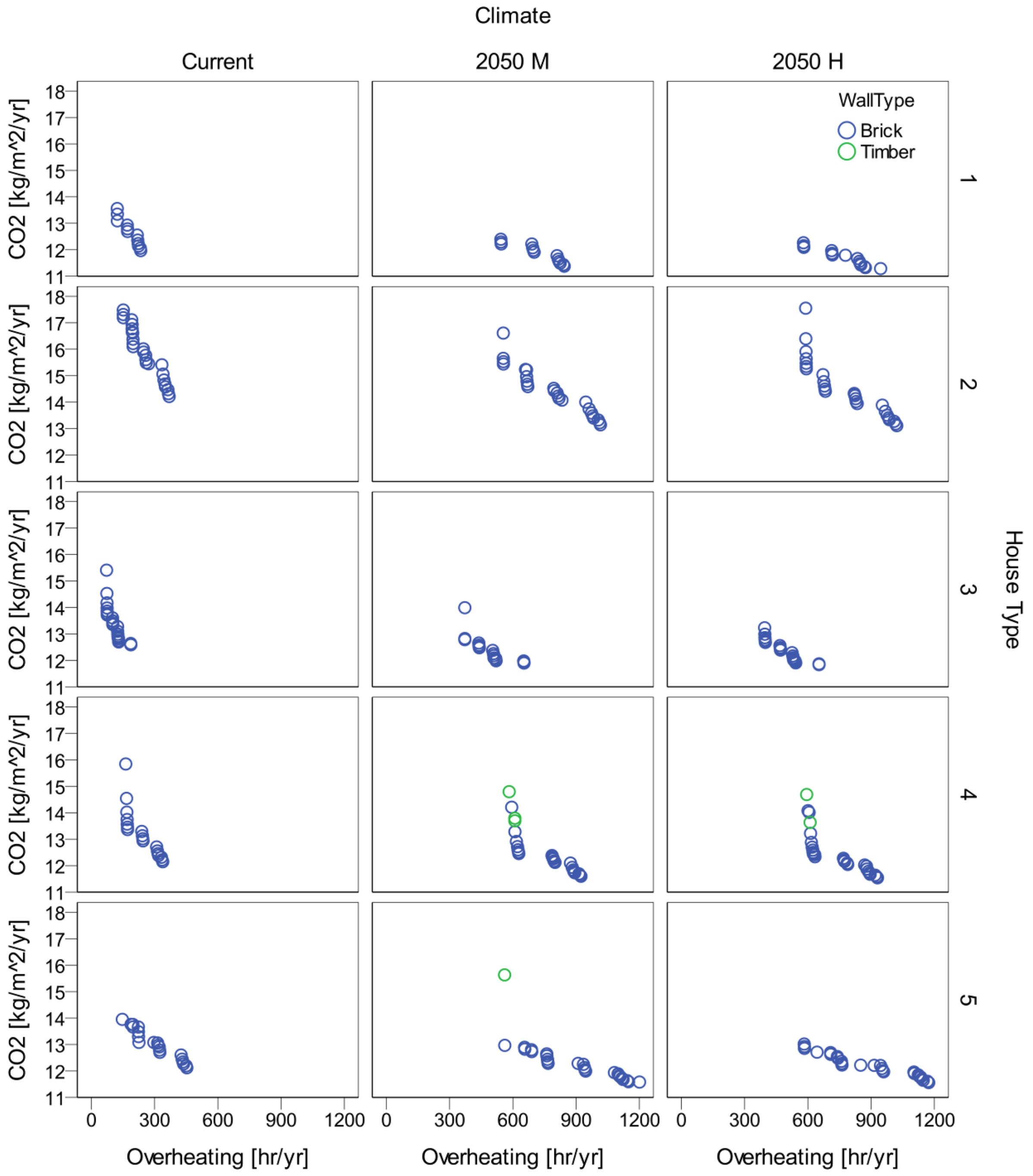

Figure 4 - Optimal plots for construction type, using same layout as Figure 3

Figure 4 shows the optimal plots for wall construction type. This shows that almost all the optimal solutions are brick constructions except for Type 4 house in the 2050s and one instance for type 5. This may be because the timber frame cannot achieve the lowest U values because of the timber fraction (even assuming a value well below typical current values).

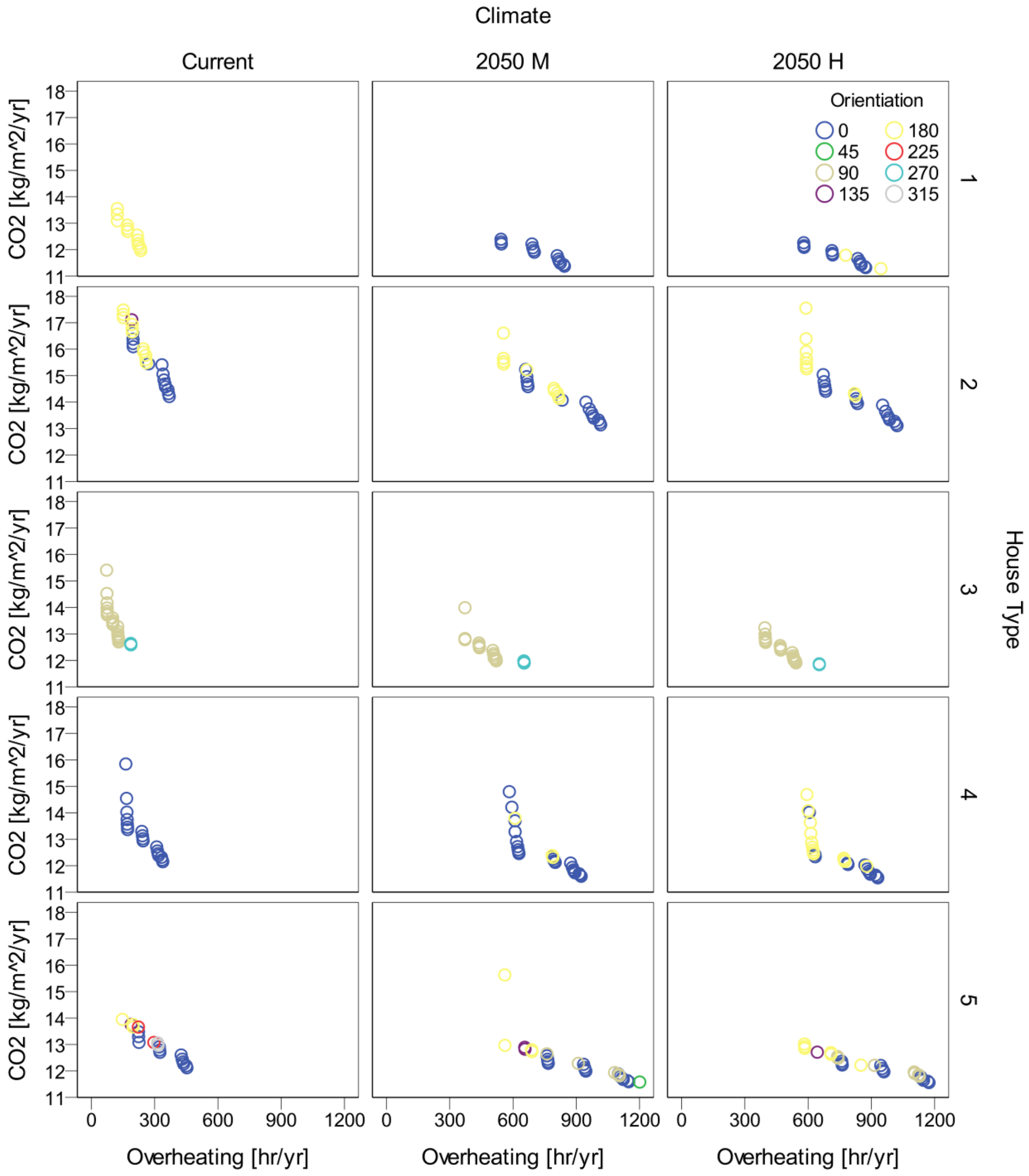

Figure 5 - Optimal results for orientation

Figure 5 shows optimal results for orientation. Interestingly for type 1, the optimal designs switch from all south facing (180°) in the current climate, to all north facing; this may be due to the change in importance from heating to overheating. Type 4 optimal results are consistently 90° orientation with three exceptions (but all of these have more overheating), while type 5 shows a wide mix of orientations. A mix of orientations for different types is expected, because of the different amounts of glazing on each façade in different designs.

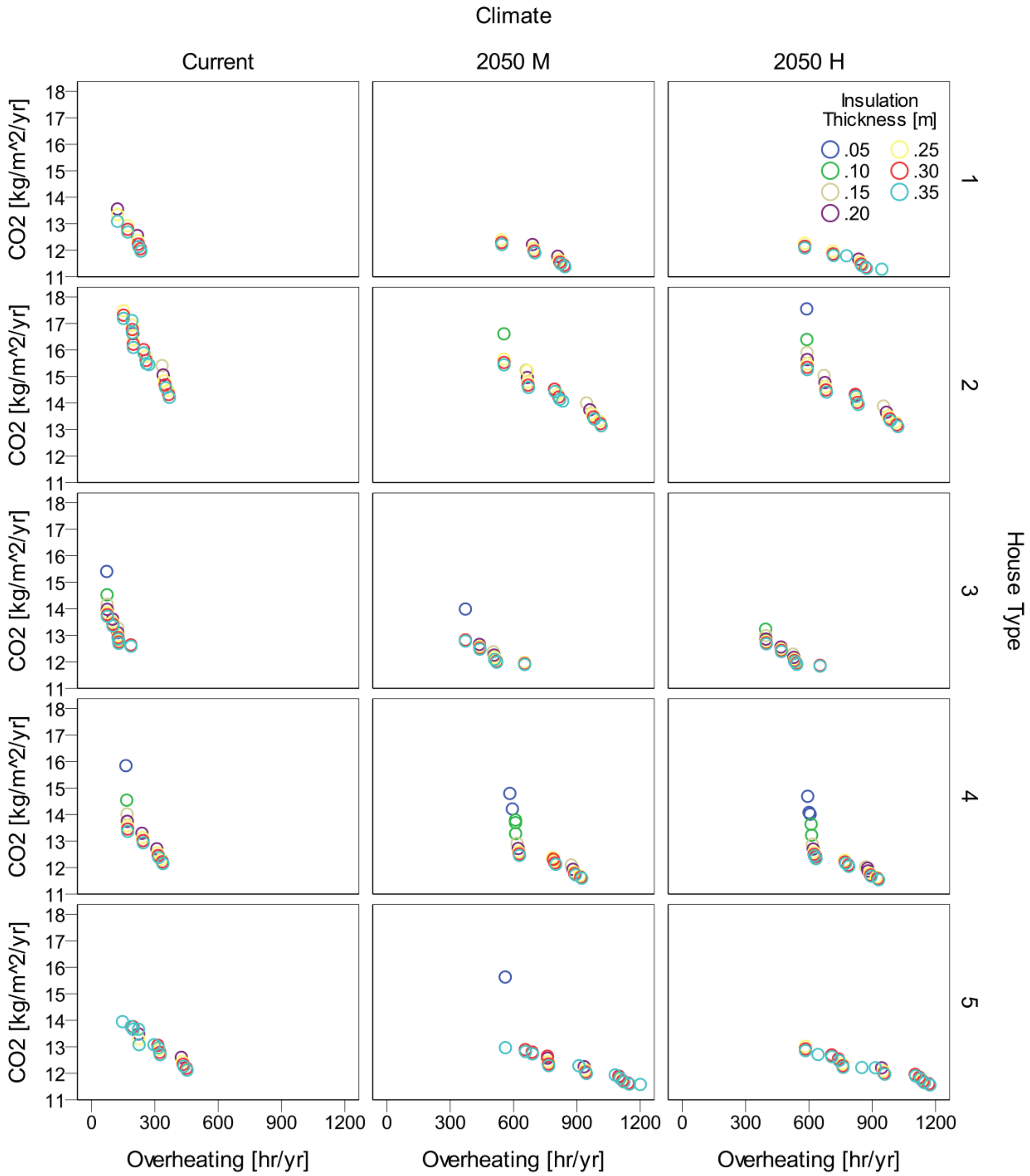

Figure 6 - Optimal results for insulation thickness

Optimal results for insulation thickness (Figure 6) show a lot of red-turquoise pairs which are very close together and represent the highest levels of insulation. These tend to have the highest overheating but lowest carbon dioxide, as would be expected. At the other extreme are designs with minimal insulation (blue circles, 50 mm insulation) which give the least overheating and highest CO2, with intermediate insulation levels and performance making up the rest of the optimal solutions. The general shapes do not vary very much between climates, except for an upward shift in overheating and a ‘stretching’ of the range of overheating hours for the 2050s along the x-axis.

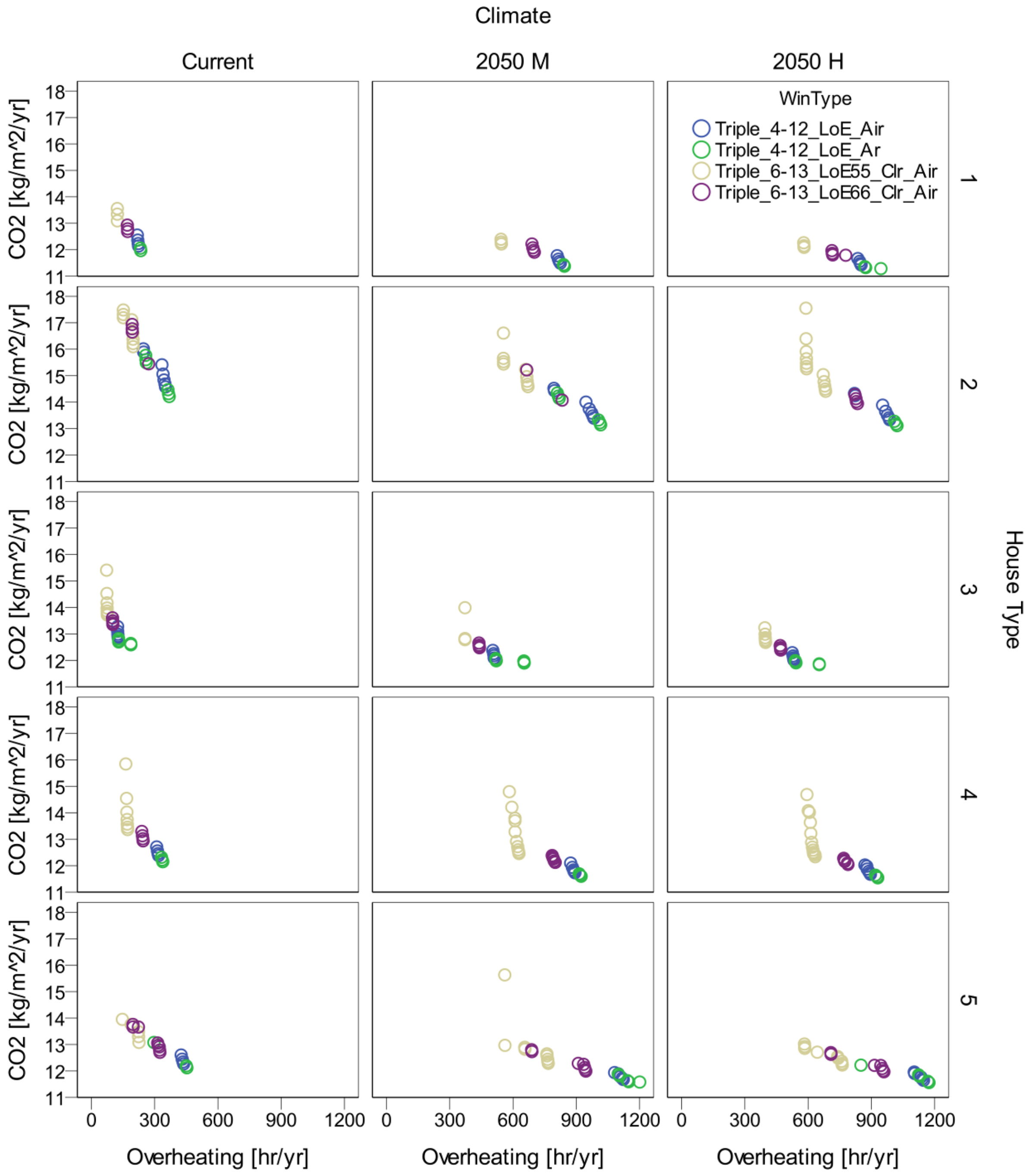

Figure 7 - Optimal results for glazing types

Results for glazing types are shown in Figure 7. Solar control glazing has a noticeable effect in reducing overheating hours (purple and khaki) compared to normal glass (blue and green), the latter having higher overheating hours but lower CO2 emissions. All the optimal results are triple glazing; this is not surprising since it has lower heat loss and lower solar gain. This suggests that the reduction in heat loss outweighs the reduced light transmittance of triple glazing, which would increase use of electric lighting. This does however not take into account the visual comfort health effects of reduced daylight.

5.0 Conclusions

This modelling exercise has shown the much greater range of information which can be presented to a designer compared to the usual practice of doing a small number of simulations for a single weather year from the current climate (i.e. a small number of probably non-optimal points on the left-hand column of the graphs shown). In particular the large increase in overheating for 2050s climate and the fact that limiting occupied overheating hours below 500 seems almost impossible within these design parameters, does call into question whether it is realistic to expect homes not to use mechanical cooling in such a climate, at least without radical design changes. The results also show distinct differences between the various house types, but the effects of the various design options are mainly as expected – the exception being orientation where interestingly a very complex set of results emerges, with large differences in optimal values in many cases and even between climates. The most surprising result is that timber frame is out-performed by masonry in almost all cases. This arises because firstly the timber fractions limit the level of insulation which can be achieved, and secondly masonry construction typically results in less overheating due the greater thermal mass (it was assumed both constructions achieved very good air tightness), when in practice this is easier to achieve with timber frame. Overall, the work demonstrates the value of this parametric approach which with software such as jEPlus, where the additional effort required compared to normal simulation is quite small, and run times are feasible on a good desktop computer in batch mode (a matter of hours).

References

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1 NHBC Foundation, Today's attitudes to low and zero carbon homes (NF40), 2012.

2 HM government, The Carbon Plan: Delivering our low carbon future, 2011.

3 BRE Passivhaus site, Passivhaus standard, outline specification, 11 December 2012, http://www.passivhaus.org.uk/standard.jsp?id=18

4 Department of Energy and Climate Change, Standard Assessment Procedure (SAP), 11 December 2012, http://www.decc.gov.uk/en/content/cms/emissions/sap/sap.aspx

5 Goodier, C. Cropper, Paul Shao, L. Porritt, S. Adapting dwellings for heat waves, Sustainable Cities and Society, 2011, 1 (2), pp. 81-90

6 Wright J.A., Heather A. Loosemore H.A., Farmani R., Optimization of building thermal design and control by multi-criterion genetic algorithm, Energy and Buildings 34 (9), 2002, pages 959–972

7 Bell M, Overend P. Building Regulation and Energy Efficiency in Timber Frame Housing, COBRA 2001 - RICS Foundation Construction and Building Research Conference, Glasgow, UK. 2001.

8 CIBSE Guide A Environmental Design, Chartered Institution of Building Services Engineers, London 2006.

9 JEPlus website http://www.iesd.dmu.ac.uk/~jeplus, 14 December 2012.

10 Prometheus climate data, university of Exeter, http://emps.exeter.ac.uk/research/energy-environment/cee/projects/prometheus/, 14 December 2012.