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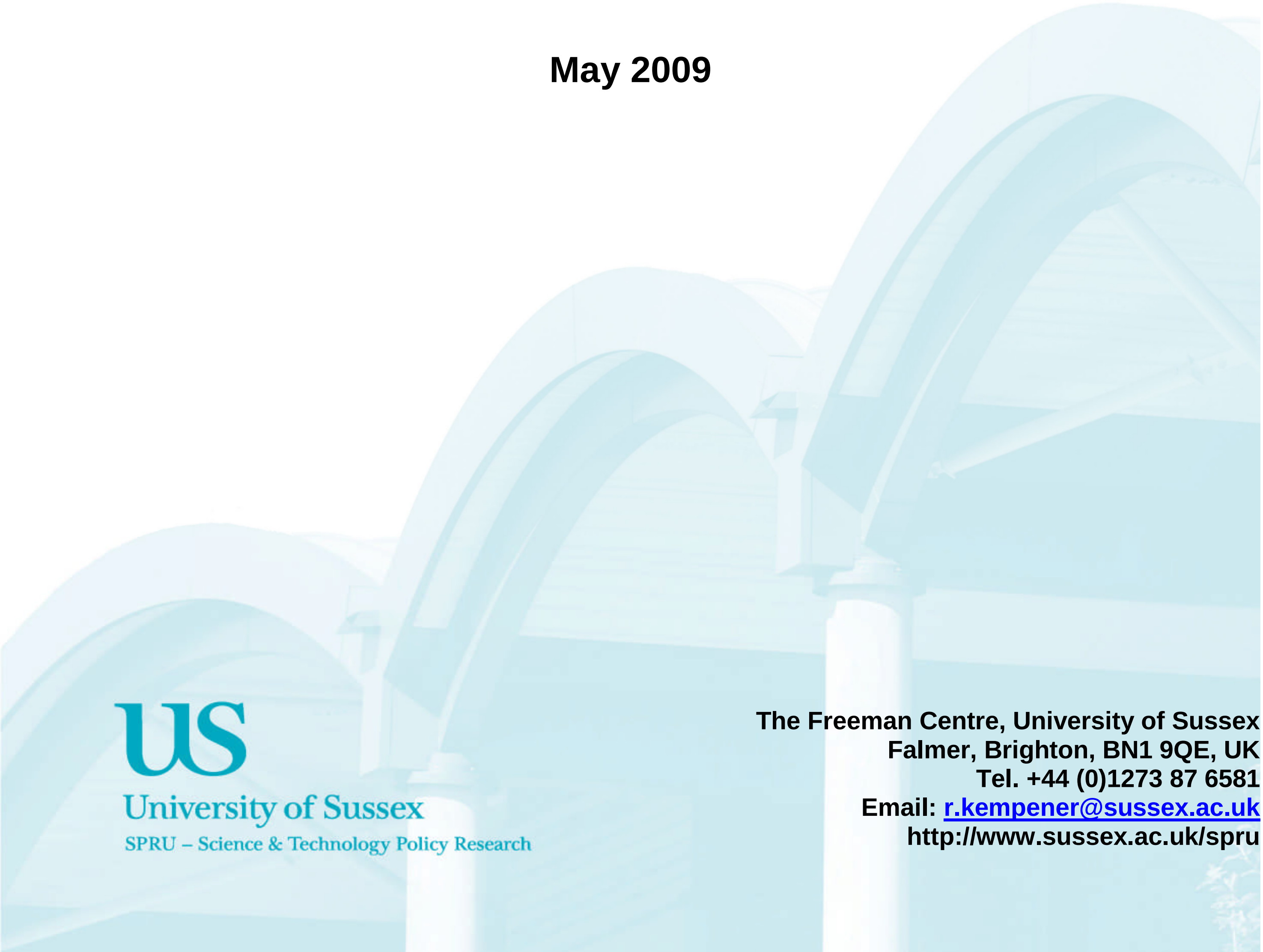

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Content

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Agent-based modelling, personal carbon trading, household behaviour, tradable permit markets

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C63; D01; O33; Q41; Q54; Q55

Abstract

Substantial changes in individual and household energy use are necessary to deliver UK's carbon emissions reduction target in 2050. Personal carbon trading (PCT) has been suggested as one of the instruments to instigate such behavioural change. It would involve allocating carbon permits to individuals and households, which would have to surrender these permits if they engage in emission-producing activities. Furthermore, they would be able to trade these permits if required. PCT is controversial and has been subject of several academic and governmental discussion papers. The analyses so far have mainly been qualitative and have focused on potential barriers associated with the introduction, implementation and operation of such tradable permit scheme, while the basic assumptions underpinning the principles of PCT remain unchallenged. This paper presents a simple agent-based model (ABM) to explore these underlying behavioural assumptions. It explores a set of interpretations of utilitarian rationality for household behaviours and its consequences for the efficiency and effectiveness of the scheme. The ABM itself is based on empirical information about household income levels, energy use, energy prices and the characteristics of several energy efficient technologies available in the UK. The results suggest that although PCT maintains emissions within a limit, it is not necessarily effective in allocating permits wherever needed. Furthermore, the scenarios show that PCT does not necessarily result in a carbon price reflecting the marginal costs for abatement technologies. Finally, the results challenge the general assumption that there is a linear relationship between household income levels and the impact of PCT on these households. The paper finishes with a set of recommendations for further research and expansion of the model.

1. Introduction[1]

In 2008, personal carbon trading (PCT) received much attention both in academic papers and political discussions. In April 2008, the Department for Environment, Food & Rural Affairs (DEFRA) concluded that the perceived advantages of PCT do not warrant active engagement and preparations for setting up a PCT scheme from a governmental perspective (DEFRA 2008). In contrast, the House of Commons brought out a different report in the same month foreseeing and suggesting an important role for PCT in achieving the Government's carbon emissions reduction targets in 2050. In response to the DEFRA report, they therefore urge for increased leadership and co-ordination from the Government in order to increase public acceptance and to address current operational difficulties through co-ordinated research activities (House of Commons 2008).

In the UK, several issues associated with PCT have been addressed in the academic literature. Kerr and Battye (2008) examined in how far PCT fits within the current and proposed UK policy framework and whether it can significantly contribute to achieving the 80% emission reduction target. Earlier research publications have focused on the operationalisation of PCT and how different allocation mechanisms could achieve an economic, effective and efficient reduction of carbon emissions by individuals, households and/or businesses (Roberts and Thumim 2006; Flemming 2007). Also, the socio-psychological effects of carbon credits on individual awareness and its impact on the effectiveness of PCT have received increased attention (Starkey and Anderson 2005; RSA 2007; Seyfang, Lorenzoni et al. 2007). Furthermore, analyses of PCT have argued that more research is needed on the role of political acceptability and public support for the introduction of a PCT scheme (Roberts and Thumim 2006; Seyfang, Lorenzoni et al. 2007; House of Commons 2008).

In summary, these reports conclude that there are a number of barriers that would affect the efficiency and effectiveness of a PCT. These barriers include, but are not limited to: 1) up front financial costs for households investing in energy efficient technologies, 2) hidden costs, 3) split incentives, 4) psychological/sociological barriers, 5) information asymmetry and 6) regulatory barriers (Kerr and Battye 2008). Accordingly, researchers and policy makers have assessed and discussed to what extent these barriers might be alleviated and/or the extent to which they affect the efficiency of a PCT. However, the conceptual ideas and assumptions behind PCT remain unchallenged. In other words, none of the researchers questions or investigates the assumptions on which the principles of PCT are based.

This paper takes a different approach and explores explicitly the assumptions and principles behind PCT. It develops an agent-based simulation model (ABM) based on empirical data about household income, expenditure and energy use in the UK. The ABM is used to evaluate how different stylised household behaviours might respond to carbon permits with regard to their household energy use, investment decisions in energy efficient technologies and holiday decisions. The model explores how these decisions affect the price of carbon permits and how subsequently the carbon price affects of investment and holiday decisions at a later stage. Different scenarios of

[1] This working paper has benefited from discussions with Sigrid Stagl, Peter Kaufmann and Steve Sorrell. Many thanks to Lee Stapleton for providing useful comments on a previous draft.

behaviour will be explored to analyse their impact on the operation, effectiveness and efficiency of a carbon trading scheme. Subsequently, the model is used to experimentally explore how different designs of the PCT either positively or negatively affect its efficiency and effectiveness.

This paper consists of six parts. The first part discusses and challenges the principles behind PCT and develops a set of research questions. The second part discusses the methodology developed to explore the effectiveness and efficiency of PCT. The third part discusses the development of the agent-based model. The fourth part presents the modelling results of some of the scenarios explored in this paper. This is followed by a discussion and finally some preliminary conclusions will be drawn as well as a number of recommendations for future research.

2. Principles of market-based instruments

PCT is a form of tradable permit trading, which in economic theory is viewed as the most superior mechanism to address environmental issues in cases where the “marginal damage cost curve” is relatively steep – ie additional pollution can have severe consequences on the environment (Woerdman 2002). Firstly, it is more effective than taxes, because the total of tradable permits forms an absolute cap or ceiling of emissions. Secondly, it is more economically efficient and transparent than regulation, subsidies and other regulatory, informational or financial incentives, because it reduces emissions wherever it is cheapest. Although some papers addressed a number of factors that can adversely affect the performance of tradable-permit systems (Stavins 1995), most literature still regards permit trading as a conceptually sound, simple and cost-effective system for pollution control.

PCT is based on this concept of tradable permit markets. The concept for PCT is as follows. Yearly, a finite amount of carbon emission allowances is allocated to individuals. Individuals will have to surrender allowances if they pursue activities that result in emissions. Those who produce fewer emissions than the number of allowances they received can sell them. Similarly, those whose activities result in more emissions than they have allowances will need to buy them. In theory, the supply and demand of carbon allowances results in a carbon allowance price that is equal to the marginal abatement costs for achieving the overall carbon cap.

The “simple” conceptual framework for PCT is based on a set of assumptions about how individuals within a carbon market operate and how the price for carbon allowances is established. These assumptions are as follows:

1. Individuals know how much emissions they emit and what the marginal abatement costs are for reducing their emissions.
2. Individuals are able to assign an economic value to activities that emit emissions.
3. Individuals are able to compare the associated economic value of their activities with the potential economic value of omitting particular activities and selling of the associated carbon allowances.
4. There are a large number of buyers and suppliers of carbon allowances.
5. The price of carbon is determined by the intersection of the supply and demand curve.

These assumptions resemble the principles used to conceptualise a ‘perfect market’ in neoclassical economic theories. It assumes that individuals are utilitarian who can measure and evaluate the utility of different alternatives and make choices accordingly, that information is available about the emissions of particular activities and it assumes that there will always be buyers and suppliers and that information. However, these assumptions are routinely violated in the real world (Conlisk 1996; Thaler 2000). For example, people behave risk aversive (Tversky and Kahneman 1981), people use heuristics rather than optimisation routines to make decisions (Gigerenzer and Goldstein 2000) and people use social norms and value to understand and interpret uncertainty (Hodgson 1988) to name a few.

On this basis, this paper critically examines the notion of utilitarian rationality and the implication of these assumptions in the context of PCT. It will assume, as in neoclassical theory, that there are no transaction costs, that there is no regulatory scheme interfering with PCT, that there are no hidden costs and that everybody is aware of the emissions associated with their activities. However, contrary to neoclassical economic theories, this paper will explicitly unpack the assumptions behind utilitarian rationality. The model will be used to explore how different interpretations of utilitarian rationality in terms of household behaviour affect the efficiency and effectiveness of the scheme. For example, at what price would an individual be willing to invest in abatement technologies? If so, what assumptions does an individual make about the carbon price in the future? How do individuals deal with the inherent risks associated with investing in new technologies? At what price would an individual be willing to give up his/her holiday? When to buy/sell allowances? Similar questions can be asked about the mechanisms by which the carbon price is determined. What happens if everybody wants to buy allowances? Will the carbon price indeed reflect the marginal costs of abatement or is it driving by social behaviours (summer and winter holidays)? In how far will individuals be able to buy/sell allowances to others? Finally, there is the complex interaction between individual behaviour creating and responding to the market, which makes it difficult to predict the effectiveness and consequences of PCT.

This paper has developed an ABM to explore some of these basic assumptions about how individuals might respond to carbon allowances and how a market might operate.

3. Methodology: an agent-based model

The analysis will take place through the development of an ABM. ABM is a quantitative computational modelling approach that simulates the actions and interactions of autonomous agents within a network. Each agent is endowed with a number of decision rules, which they apply if their current situation within the network requires so. The outcome of these actions gives rise to system wide patterns. Simultaneously, these system wide patterns (in the case of PCT this represents the market price for carbon allowances) affects the behaviour and interaction of individuals at a later stage. ABM is particularly useful for exploring the performance and evolution of systems that are affected by local interactions between individuals - otherwise called ‘complex adaptive systems’ (CAS). Both the effects of individual behaviour on the exchange of allowances and the interaction between individuals through the establishment of social norms could play an important role in the performance and success of a PCT scheme.

The agents within the ABM represent a set of households. Each household is assumed to act as a discrete, autonomous and coherent decision maker consisting of an equal number of household members[2]. These adults have a monthly income, they have monthly energy expenditures with associated emissions and they can decide to go on holiday. The households can differ in terms of income level, monthly energy use and number of anticipated holidays per year. Each household has particular savings depending on their income, consumption patterns and expenditure on energy and/or emission allowances. Households can adjust their behaviour by reducing the number of holidays or by investing in energy saving appliances. The model assumes that there no transaction costs, it assumes that households are aware of the carbon emissions associated with particular behaviours and that there are no other regulatory schemes interfering. Furthermore, it assumes that there are no hidden costs or split incentives[3].

The model is sequenced as follows. Each year all households receive an equal number of allowances, which totals last year's emissions with a particular reduction. At the start of the year they determine the costs (including associated emissions credits) of their monthly energy use (electricity, gas and petrol) and potential UK or international holiday. Depending on their objectives, their savings and the number of credits allocated they plan their holidays.

The sequence of decision making is similar for each household. At the first month of the year, households determine how much credits are required for monthly energy use. Furthermore, they build in a contingency of 5% of their total annual emissions (excl. emissions associated with holidays). Subsequently, they plan and buy their holidays. They only require surrendering their carbon credits at the time of their holiday. Finally, each household goes through the following set of activities and decisions at the beginning of every month: they receive their monthly income, pay their monthly non-energy expenditures, pay their energy bills and surrender the associated carbon credits. If they cannot pay their energy bills, they face 'fuel poverty' and will not receive respectively electricity, gas or petrol. Fuel poverty, in this sense, does not relate to the UK definition of 10% or more of annual income spent on fuel as defined by DTI (2001), but to a 'relative' fuel poverty in that households cannot get hold of carbon credits to purchase energy. The rest of the paper will use the term 'relative fuel poverty' to depict this difference. Subsequently, they determine whether they are going on holiday that particular month and surrender their associated credits. If they do not have the required number of credits, they will have to cancel their holiday and they will not receive any reimbursements for the costs. At the end of the month, they determine how much credits they need until the rest of the year and determine their buying/selling price for credits.

In short, the following list provides an overview of the different actions/decisions of households:

1. they evaluate the energy and associated emissions required for their activities for the remainder of the year (including a contingency);
2. they evaluate the number of allowances they have;

[2] Each household is assumed to be equal in terms of the number and configuration of household members (ie two adults and two children) and their behaviour is 'as a unit'. In other words, their holidays, travels and energy use within the household are always used together.

[3] Using this approach, we intend to stay as close as possible to the neoclassical assumptions about tradable permits in order to investigate the basic assumptions of utilitarian rationality behind the theory. The consequences of potential barriers will be included and examined at a later stage.

3. they evaluate the market price for allowances;
4. they evaluate their savings;
5. they evaluate and potentially invest in carbon abating technologies;
6. they determine the quantity and price they are willing to buy/sell allowances on the market.

After each household has determined whether to buy, sell or not trade on the carbon market, the carbon price is determined according to the equilibrium price associated with the demand/supply curve (see figure 1). The demand/supply curves are depicted step-wise rather than linear to emphasise that each buyer and supplier of carbon credits have a discrete number of carbon credits available for a particular price. The sum of the individual demand/supply creates these curves. Subsequently, those households that are willing to trade allowances for the equilibrium price will either buy or sell their allowances for the established equilibrium price. If a particular household has excess allowances at the end of the year, they will be lost. Finally, if a particular household runs out of allowances and savings, the household will experience 'fuel poverty' and will not be able to receive energy for that particular month. Similarly, if a household has planned a holiday in a particular month but does not have enough carbon credits, the holiday will be cancelled (and no refund will be reimbursed).

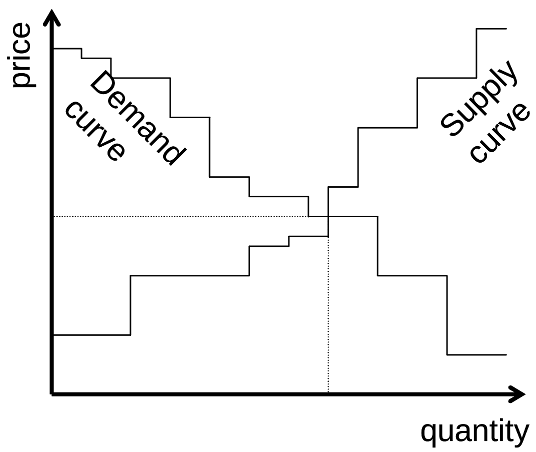


Figure 1. The market price of carbon is determined by the equilibrium between demand and supply.

The efficiency and effectiveness of the PCT will be evaluated on the basis on the efficiency and effectiveness criteria as used in neoclassical economic theory to evaluate permit trading markets (Woerdman 2002):

1. Effectiveness: Will the absolute amount of emissions be reduced over time?
2. Efficiency: Does the carbon price represent the marginal costs of abating emissions?

4. Model development

The model is developed using AnyLogic^{TM} software. The initial data set of household expenditure is obtained through the latest "Family Expenditure Survey" (FES) of the

Office of National Statistics (ONS) in the UK (National Statistics 2008). The FES 2005-2006 has detailed information about weekly family expenditure including expenditure on electricity, gas, petrol, public transport and national and/or international holidays. The data is specified according to 10 household income categories. This empirical information is used to initialise the model, although the number of categories within the model has been reduced to five. The absolute energy use of each household income category is determined by using electricity, gas and petrol costs in 2006. The initial data representing the different households is presented in table 1.

	Household category L	Household category L-M	Household category M	Household category M-H	Household category H
Percentage	20	20	20	20	20
Monthly income (£)	895	1466	2205	3225	5868
Non-energy related expenditure[4] (£)	675	1146	1536	2064	3152
Monthly energy costs[5] (£)	77	133	163	202	283
Monthly electricity use (kwh)	209	264	295	323	390
Monthly gas use (kwh)	1182	1438	1595	1773	2245
Monthly petrol use (ltr)	28	72	96	128	191
Initial savings (£)	125	156	432	839	2228
Yearly holiday expenditure[6] (£)	305	657	1117	1699	3007
Emissions UK holiday (kg)[7]	250	250	250	250	250
Emissions overseas holiday (kg)[8]	2640	2640	2640	2640	2640
Cost UK holiday (£)	500	500	500	500	500
Cost overseas holiday (£)	1500	1500	1500	1500	1500

Table 1. Characteristics of households.

[4] Food, apparel, health and recreation.
[5] Transport and housing
[6] Travel and accommodation
[7] Holiday by car travelling 1000 km.
[8] Holiday by airplane travelling 2000 km.

Table 2 presents the energy costs and associated CO_2 emissions on which the household expenditure on energy-related activities (heating the house, electricity for appliances and/or petrol use) are based. Initially, the energy costs are considered to be constant over the analysis, however modelling shows that different growth profiles for energy costs can have an important impact on personal carbon trading.

Characteristics of environment	
Energy costs electricity (£/kwh)	0.12
Energy costs gas (£/kwh)	0.07
Energy costs petrol (£/ltr)	1.5
CO_2 emissions electricity (kg/kwh)	0.12
CO_2 emissions gas (kg/kwh)	0.07
CO_2 emissions petrol (kg/ltr)	1.5

Table 2. Costs and associated CO_2 emissions for electricity, gas and petrol.

Table 3 presents the technologies that are considered within the model. Currently, households can choose between three technologies each representing a particular category of emission-reducing technologies for households.

	Technology 1	Technology 2	Technology 3
example	Cavity wall installation	Solar thermal water panels	PV panels
Capital investment costs (3)	500	4000	24000
Savings	15% savings on heating	50% savings on hot water use	100% electricity use savings
Relative gas use reduction (%)	11	13	-
Relative electricity use reduction (%)	-	-	100

Table 3. Characteristics of energy saving technologies.

4.1. Decision rules

In principle, the households have to make four decisions:

1. the amount of international and UK holidays they plan throughout the year;
2. when to investment in emission-reducing technologies;
3. determine the price of carbon;
4. the marginal price for selling carbon credits;
5. the marginal costs for buying carbon credits.

Their decisions depend on the circumstances of the household (income, savings, energy use and costs), their objectives and interests of the household. Furthermore, it depends on the information that is provided to them. This paper explores three different behaviours that might be expressed by households. They are labelled as 1) economically focused households, 2) environmentally conscious households and 3) socially driven households. Each of these behaviours is an interpretation of utilitarian rational behaviour, because they all use information about prices and the consequences of their activities to the environment to choose their optimal behaviour. However, the objectives of these three behaviours differ substantially. None of these behaviours is assumed to reflect the true behaviour of households, but they are chosen to represent a large spectrum of behaviours possible.

The specific decision rules that are used within each of these different behaviours are described in table 4.

	Behaviour 1: economically focussed	Behaviour 2: environmentally conscious	Behaviour 3: socially driven
Nr of holidays	Only go on holiday if the costs of the holiday is less than the associated carbon emissions cost. Only go on holidays if the savings budget allows it (including costs for buying additional credits).	Only go on 1 UK holiday per year if the savings budget allows it (including costs for buying additional credits).	Plan as much holidays as possible as long as the savings budget allows it (including costs for buying additional credits)[9].
Investment in technology	Invest in the technology if the payback time is less than 2 years	Invest in the technology that reduces the most emissions (as long as it is within the savings budget)	Do not invest in emission-reducing technologies
Determine the carbon price	Use the current carbon price	Use the current carbon price	Use the current carbon price
evaluate their savings;	Check the total amount of savings available	Check the total amount of savings available	Check the total amount of savings available
Marginal costs for selling credits	The price for selling is equal to the marginal returns required for an investment in technology; if no technology is available, the price depends on whether they can earn an UK holiday by selling their credits	The price for selling is equal to the marginal returns required for an investment in technology; if no technology is available, the price depends on whether they can earn an UK holiday by selling their credits	The price for selling is equal to the marginal returns required for an investment in technology; if no technology is available, the price depends on whether they can earn an UK holiday by selling their credits
Marginal costs for buying credits	The price for buying credits is determined by required credits and available savings.	The price for buying credits is determined by required credits and available savings.	The price for buying credits is determined by required credits and available savings.

Table 4. Specific decisions rules for household behaviour.

4.2. The carbon market

The carbon market is represented by a single authority, which gathers information about the price and quantity that households are willing to buy/sell credits for. Each household

[9] An upper limit of 4 holidays per year is implemented.

receives the equilibrium price as determined by the intersection of the supply and demand curves. Household that offer credits above the equilibrium price will not sell their credits and households that demand credits below the equilibrium price will not receive credits.

4.3. The authority

In the first year, the authority issues the exact amount of allowances that covered last year's emissions. The credits are allocated equally over the households. After the first year, the authority reduces the credits by 10% per year. This means that the number of credits households receive is reduced by 10% each year.

5. Results

The purpose of the model is to analyse and evaluate how a personal carbon trading scheme would result in a price for carbon and a change in behaviour by households. The model is simulated over a 10-year time frame.

Four experiments are conducted:

1. the evolution of a carbon market if all 10 households are economically focused;
2. the evolution of a carbon market if all 10 households are environmental conscious;
3. the evolution of a carbon market if all 10 households are socially driven;
4. the evolution of a carbon market with random distribution of behaviours over 10 households;
5. the evolution of a carbon market with random distribution of behaviours over 100 households;
6. the evolution of a carbon market with random distribution of behaviours over 1000 households;

These six experiments essentially address two different research questions. The first research question is the importance of household behaviour on the effectiveness and efficiency of a personal carbon trading scheme. Three different scenarios (experiment 1-3) are developed which each analyse distinctly different behaviours. The second research question is how the scope of a personal carbon trading scheme influences its effectiveness and efficiency. Experiments 3-6 explore scale dependency by evaluating the carbon market with 10, 100 and 1000 participants. It should be mentioned that those experiments that consist of random distributed behaviours have only been simulated once. Multiple simulations runs can provide vastly different carbon market patterns, because the behaviours are randomly allocated over the different household income categories. However, in this instance the range of different evolutionary pathways is of less importance. Instead, the focus is on the generic differences between the carbon markets if the number of participants is scaled up.

The standard setting for the six experiments is as follows:

Experiment	**1**	**2**	**3**	**4**	**5**	**6**
behaviour	economic	environm.	social	random	random	random
% low income	20	20	20	20	20	20
% low-middle income	20	20	20	20	20	20
% middle income	20	20	20	20	20	20

% middle-high income	20	20	20	20	20	20
% high income	20	20	20	20	20	20
contingency (%)	5	5	5	5	5	5
# of households	10	10	10	10	100	1000
Energy prices	constant	constant	constant	constant	constant	constant
Max. # holidays	4	4	4	4	4	4

Table 5. Settings for the experiments.

The results are displayed in two sets. The first set of results provides an overview of the development of the carbon market (price of carbon, size of market) and the performance of the personal carbon trading scheme (yearly allocation of credits and total emissions of households). The second set of results provides an indication of the consequences of a personal carbon trading scheme on the different household income groups, in particular the uptake of energy efficient technologies and fuel poverty. However, it should be noted that the consequences for households within a particular household income category may vary significantly depending on their behaviour relative to the behaviour of other households within the scheme. The full set of results is provided in the appendix.

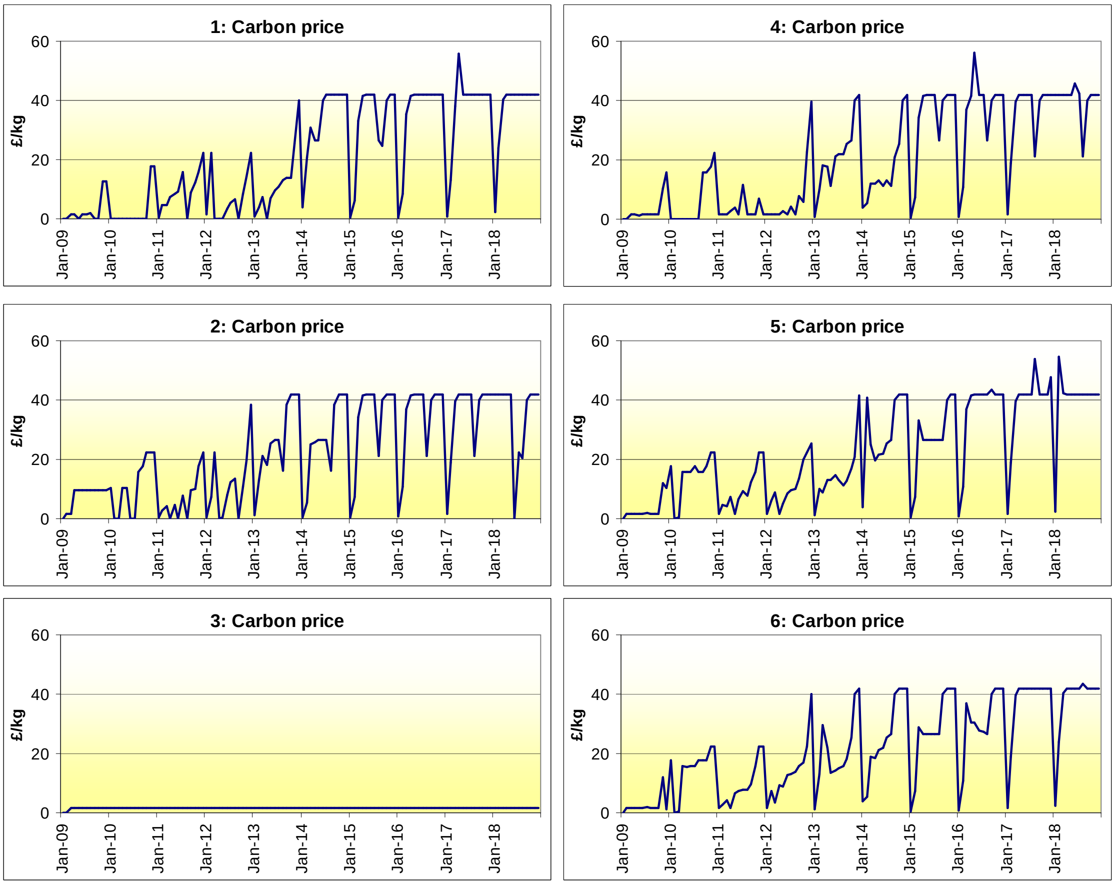


Figure 2. Development of carbon price.

Figure 2 shows the development of the carbon price under the different experiments. It shows that the carbon price within PCT can reach levels that are 1000 times higher than currently experienced in the European emissions trading scheme (the y-axis shows carbon prices in pounds/kg). The height of the carbon price is of less importance here than the actual mechanism by which it is established. In each behavioural scenario, households base their buying and selling prices on the basis of the marginal costs of technologies, except when they do not have the option to invest in technologies (see table 4: if household cannot invest in technologies, they attempt to earn a holiday by selling their permits). The main observation is that it is opportunistic behaviour that drives the carbon price rather than the marginal costs of abatement technologies. Furthermore, it shows that there is large variation in the carbon price, which is related to the allocation of carbon credits at the beginning of the year. Finally, it shows that the carbon prices increases with a reduction in carbon allocations.

Scenario 3 shows that a carbon price is not always established. In this scenario, all households are socially driven and therefore attempt to maintain a lifestyle with many holidays. Under these circumstances no carbon price is established, because all households want to buy credits and no households want to sell credits. Furthermore, more detailed analysis of the establishment of the carbon price has shown that under particular circumstances the demand and supply curves do not intersect and therefore no equilibrium price is established. In other words, the returns that suppliers require for their credits is higher than buyers are willing to pay.

Figure 3 shows the market size of the carbon trading scheme.

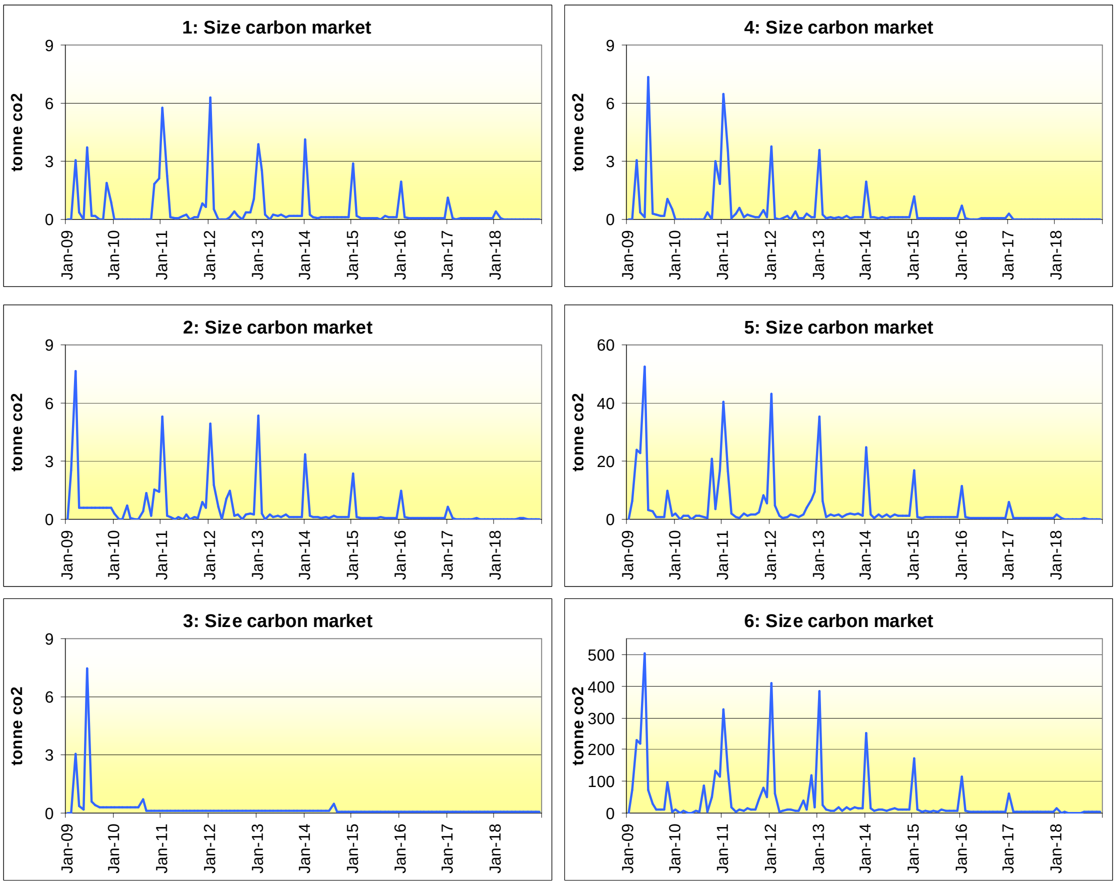


Figure 3. Market size of the carbon trading scheme.

The results show similar patterns for the different scenarios. Peak trading and peak pricing occurs at the beginning and end of the year and the volume of traded carbon credits reduces over time. Although the number of allocated credits is reduced by 10% per year, the market volume of traded credits reduces proportionally higher.

Figure 4 shows the total carbon emissions in each scenario as well as the number of allocated carbon credits in each year. First of all, the results show that the cap is always reached, which means that there are no emissions besides those that are credited for. More interestingly, however, is how the cap is reached. The results show different emission patterns (reflected in the shape of the triangles) throughout the year. This suggests that different behaviours result in different ways of reducing carbon emissions. This is shown mostly clearly when comparing the shape of the emission profile in scenario 2 (environmentally conscious behaviour) and scenario 3 (socially driven). In scenario 2, emissions are reduced throughout the year, while emissions in scenario 3 are reduced at the end of the year. In the latter case, the reduction of emission is not a function of behaviour change or investments in technologies, but is determined by households facing fuel poverty. Furthermore, the results show that not all credits are used even when one corrects for any contingency percentage used by individual households. This means that credits do not diffuse through the market to those households that require additional credits at the end of the year.

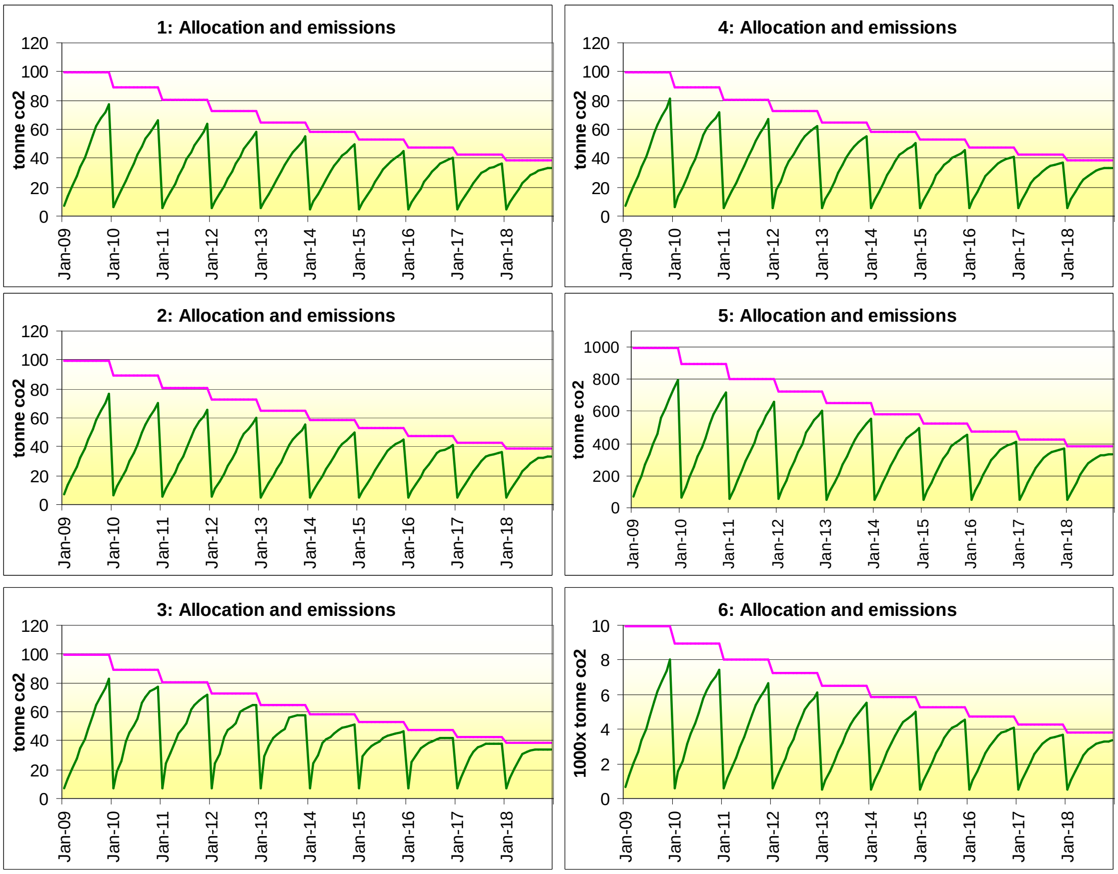


Figure 4. Allocation of credits and emissions emitted by households.

Finally, figure 5 & 6 show the fraction of households that experience fuel poverty throughout the year (with 1 reflecting a situation in which all households experience fuel poverty). Figure 5 shows average fuel poverty for all households, while figure 6 differentiates fuel poverty within the different income categories. It should be noted that in the context of this analysis fuel poverty does not mean that household cannot afford their fuel, but that they do not have the ability to obtain the credits required for purchasing the fuel.

Figure 5 show that in all scenarios households experience fuel poverty. Lowest levels of fuel poverty are observed when households behave environmentally conscious even if they have invested in all the carbon abatement technologies available (see figure 7). Their requirements for having at least 1 UK holiday per year means that it is the higher income levels with larger monthly energy uses that experience fuel poverty (see figure 6).

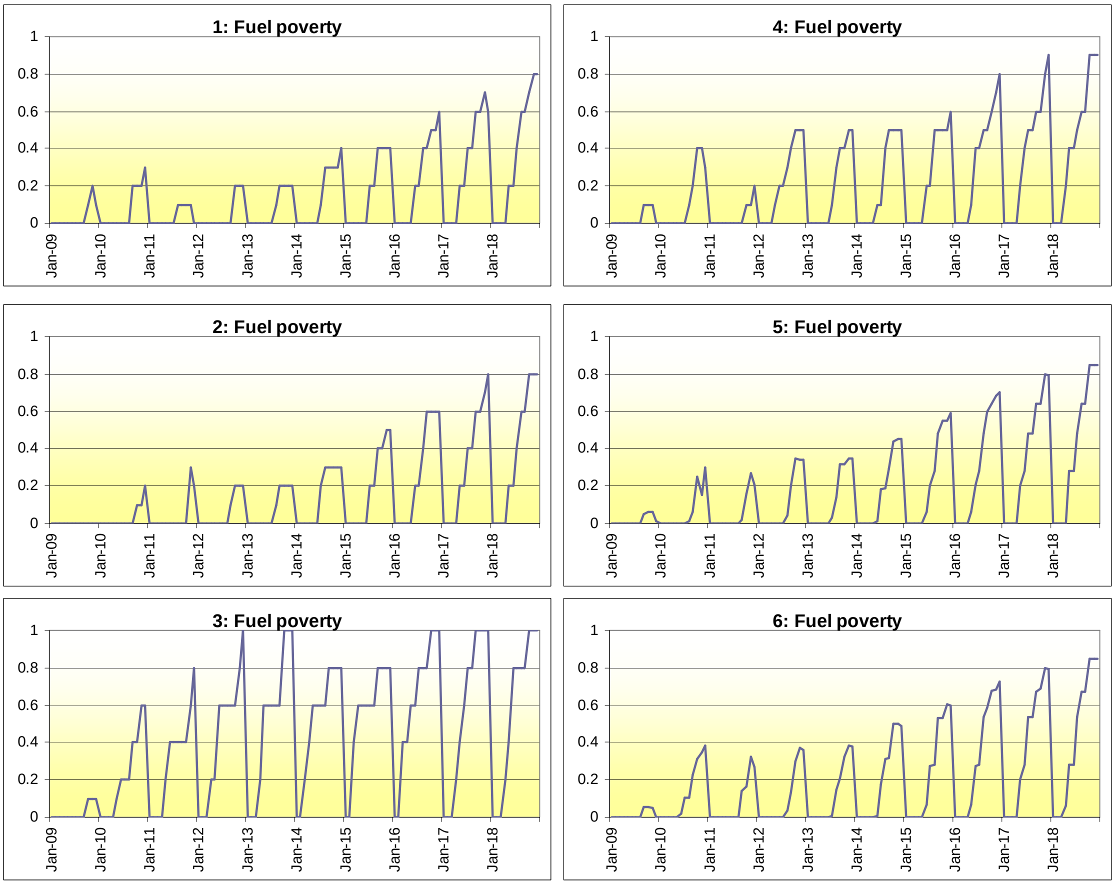


Figure 5. Percentage of households facing fuel poverty.

Figure 6 shows how fuel poverty is distributed over the different income categories. Surprisingly, it is the higher income households (H) that are not able to obtain the level of credits required to maintain their higher monthly energy use irrespective of their investment in carbon abatement technologies (see figure 7). Furthermore, it is interesting to see that neither the lower income households (L) or the higher income households (H) are the most vulnerable to fuel poverty, but it is the middle-high (MH) income levels that experience the highest levels of fuel poverty. These households use proportionally more energy than the lower and middle income households, but they receive far less income than the higher level income households. This means that they are buyers for credits, but they can only obtain credits after the higher income households have satisfied their needs. Finally, it is interesting to see that the more participants are operating within a PCT, the later the lower income households experience fuel poverty. A larger portion of participants provides lower income households with a proportionally higher level of credits at the beginning of the analysis, therefore reducing their risk for fuel poverty. Finally, it should be noted that all these observations are tentative and highly sensitive to the exact distribution of behaviours within each income category (see table A1).

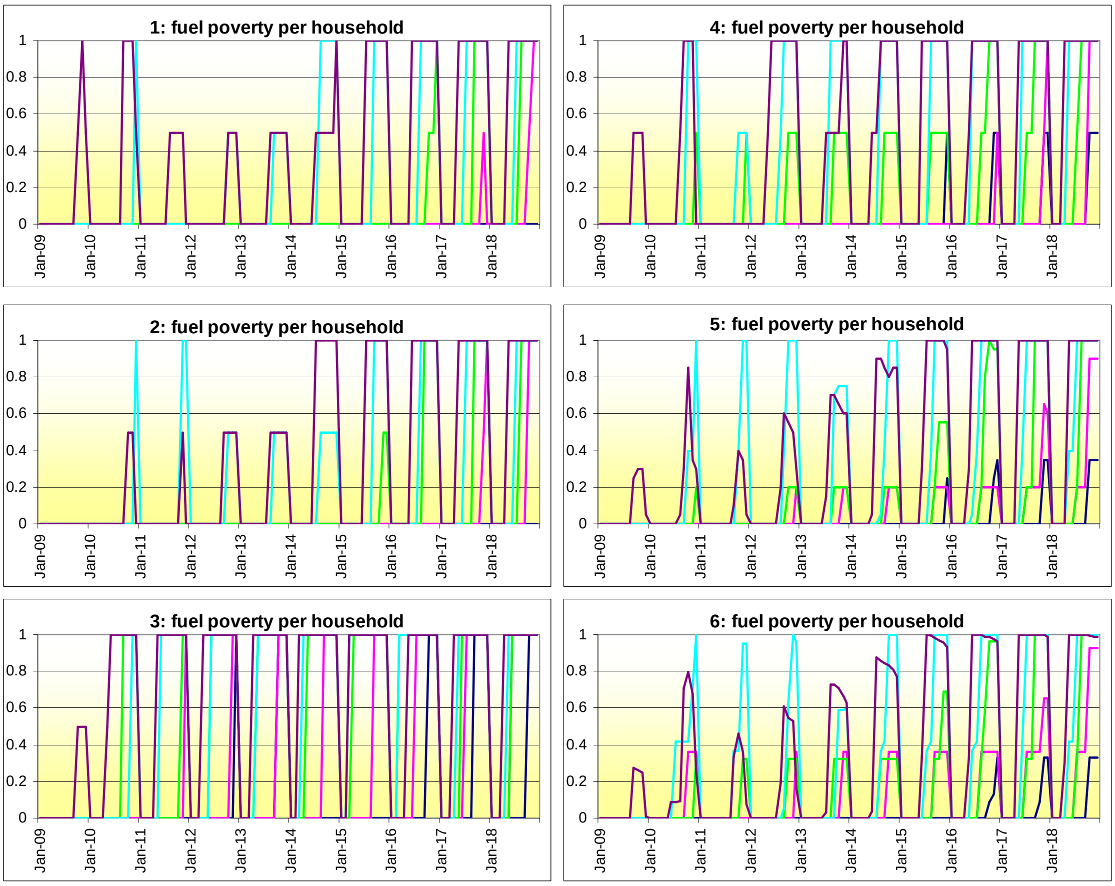
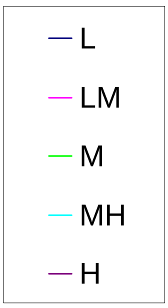


Figure 6. Percentage of households facing fuel poverty per household income category.



Finally, figure 7 shows the uptake of carbon abating technologies by households whereby a level of '1' suggests an uptake of a particular technology by all households. The results in scenario 1 and 2 suggest that it would be economically feasible and possible for all households to install all three technologies. Furthermore, the results show the different stages by which different income categories have the opportunity to invest in carbon abatement technologies. However, scenario 3 suggests that no technologies will be installed if households attempt to maximise their holidays rather than focussing on carbon reductions. Scenarios 3 to

6 show the uptake of technologies when faced with mixed behaviour. It shows a much slower and no complete uptake of all carbon abatement technologies, however high ratios are possible.

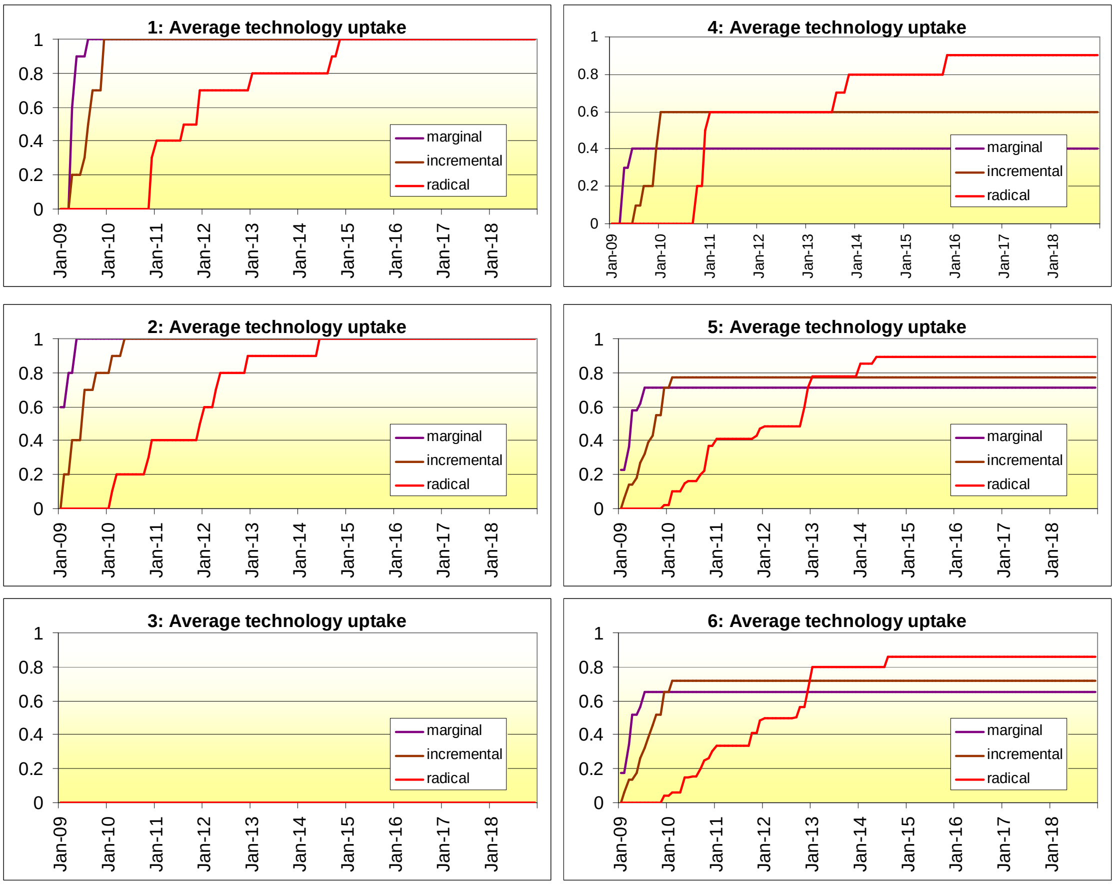


Figure 7. Average fraction of technology uptake per household.

The experiments presented and discussed in this paper provide only the preliminary results of the analysis using ABM. Other experiments that are currently conducted are:

1. the role of different income distributions;
2. the role of increasing energy prices;
3. the role of technology development (incl. learning curves);
4. the role of social institutionalisation in the decision making processes of households;
5. the role of different allocation mechanisms for carbon credits;
6. the role of energy conservation through behaviour;

6. Efficiency and effectiveness of PCT

Tradable permit markets have been favourable policy instruments to effectively and efficiently internalise external environmental costs associated with particular activities.

The modelling results show that both criteria are not necessarily met in the case of a personal carbon trading scheme. The results (see figure 2) show that absolute emission reductions are achieved through a carbon trading scheme. However, they are not necessarily reduced effectively. First of all, there are often considerable gaps between what could be emitted and what is actually emitted. This means that some households have excess allowances at the end of the year, but that the market does not provide any opportunity to sell these allowances to other households. Secondly, the profile by which the emissions reductions are achieved shows that the emissions reductions are not adequately achieved over the total timeframe of the year. In many circumstances, the emission reduction targets are met because of fuel poverty at the end of the year rather than through a change in behaviour, the installation of new energy efficient technologies and/or the exchange of allowances between different households.

The second condition for evaluating the personal carbon trading scheme is efficiency. A tradable permit market is efficient if the permit price reflects the marginal costs of those technologies/behaviours that would reduce the environmental impact. Table 6 provides the marginal costs for the 3 technologies considered in this study.

	Technology 1	Technology 2	Household 3
example	Cavity wall installation	Solar thermal water panels	PV panels
Household L	1.7	11.3	22.2
Household L-M	1.4	9.3	17.6
Household M	1.3	8.4	15.7
Household M-H	1.2	7.5	14.4
Household H	0.9	5.9	11.9

Table 6. Marginal costs for carbon reducing technologies in £/kg[10].

The marginal costs for each technology are different for the different household income categories, because each household category has different profiles of energy use. The carbon price that is established in any of the scenarios market does not reflect the marginal costs of these technologies. Although the carbon price profiles tend to increase in the latter years of the personal carbon trading scheme, the carbon price does not reflect the most efficient pathway towards reduced carbon emissions through the implementation of gradually more expensive technologies. Instead, the carbon price is heavily affected by when the credits are allocated, when they go on holiday, their individual objectives and their savings. For example, in many cases the households are not able to afford the up front costs of investing in carbon saving technologies. Household do not have sufficient savings for the upfront financing of technologies, while the returns through reduced emissions will only become available at a later stage throughout the year. In such cases, households do not use the marginal costs associated with carbon reductions as the selling price for their credits, but instead base their selling price on whether they can earn UK holidays by selling their credits[11].

[10] The marginal costs are only calculated on the basis of their carbon saving potential without considering the additional benefits it would bring to a household through reduced energy costs.

[11] Obviously, this is a very simplified rule that has been introduced in the model. However, it reflects the notion of the indirect rebound effect; households and organisations often spend their savings in one area on products and activities in other areas (ie leisure activities).

The results also show that there is no coherent pattern of technology adaptation. Only in the scenarios where all households behave either economically rational or environmental conscious (scenario 2 and 3), the uptake of technologies follows a logic sequence with marginal technologies adopted before incremental technologies and radical technologies adopted last. In the scenarios with mixed behaviours (scenarios 4, 5 and 6), the diffusion of carbon saving technologies is not linear. As a consequence, the carbon price does not reflect the marginal costs for carbon abatement.

Several studies have suggested that personal carbon trading should not be seen as an economic-derived instrument, but as a way of providing households with information about their behaviour and associated consequences for carbon emissions (RSA 2007). The preliminary modelling results in this study, however, suggest that a personal carbon trading scheme implemented on the principles of a ‘cap & trade system’ as suggested in the economics literature would not provide such information. Instead, households are faced with intrinsic uncertainties about the value of carbon abating technologies in the future, the price they receive/pay for credits and the availability/price of credits at later stages throughout the year. In other words, these preliminary results show that more understanding is required about the exact principles on which a PCT scheme would operate and its consequences for the behaviour of individual households.

7. Conclusions

This paper suggests that there is still a lack of critical analysis and understanding how tradable permit markets affect the behaviour of individuals, households or organisations operating within these markets. The principles of tradable permit markets have been developed within a framework of a perfect market with little consideration for the intrinsic complexities associated with multiple actors operating in an imperfect world. In other words, utilitarian rationality has been assumed to be the main mechanism behind the behaviour of agents operating within a tradable permit market without considering what utilitarian rationality actually means. Instead, much research focuses on details about the implementation and/or potential behaviours of individuals within a PCT without any clear understanding of how these complexities might affect the performance of the market as a whole.

This paper has developed an empirically based ABM platform to analyse and explore the basic assumptions that form the basis for a carbon trading scheme. The model allows for exploring how different behaviours, implementation strategies and market mechanisms might affect the effectiveness and efficiency of a PCT. Furthermore, it allows for exploring the potential consequences of PCT on the energy behaviour of households in the UK over a longer period of time. The behaviours explored within this paper are still relatively simple, but the results show the potential for future explorations.

The preliminary results have shown that none of the scenarios explored results in a PCT scheme whereby the carbon price reflects the marginal costs of carbon abatement technologies. Furthermore, it has shown that the carbon market does not necessarily operate effectively. Households are reluctant to trade credits and/or are unable to obtain the required information to make rational decisions about when to buy/sell credits for what price. Furthermore, it has shown that in a PCT scheme fuel poverty is not necessarily associated with the costs of energy, but that fuel poverty can also occur if high income households are unable to obtain credits. Finally, the results have shown that irrespectively of investments in carbon abatement technologies, changes in the behaviour of households are required to achieve the required levels of carbon emission reductions without fuel poverty.

The results presented in this paper are only the start of a larger set of experiments that can be conducted to more clearly understand how PCT might affect energy use in households.

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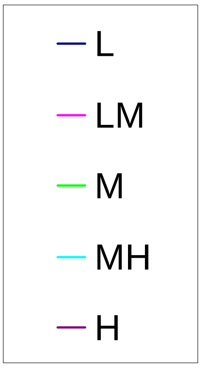
Appendix

The following figures provide additional modelling results on which this paper is based. The results are specified according to the different income categories explored within the model.



The legend for the figures is as follows:

- dark blue: low income households
- pink: low-middle income households
- green: middle income households
- light-blue: middle-high income households
- purple: high income households.

Furthermore, the fraction of economic driven, environmentally conscious and socially driven households within each income category for experiments 4,5 and 6 is provided in table A1.

Household category	L	L-M	M	M-H	H
	Experiment 4				
Economic	1	1	0.5	0	0
Environmental	0.5	0	0	0	0
Social	0.5	0	0.5	1	1
	Experiment 5				
Economic	0.35	0.45	0.2	0.35	0.4
Environmental	0.3	0.35	0.6	0.25	0.3
Social	0.35	0.2	0.2	0.4	0.3
	Experiment 6				
Economic	0.33	0.325	0.375	0.3	0.375
Environmental	0.34	0.315	0.305	0.285	0.29
Social	0.33	0.36	0.32	0.415	0.335

Table A1. Percentage of behaviours within the different income categories in the three random experiments.

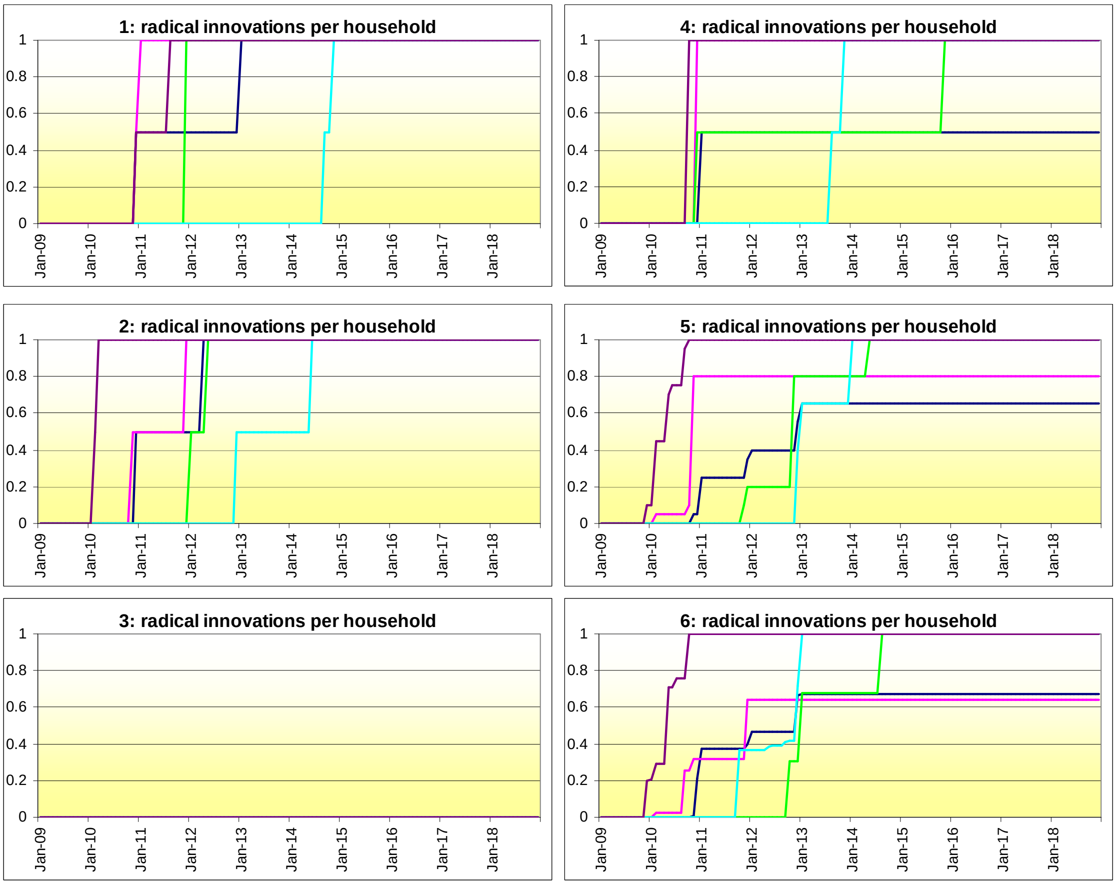


Figure A1. Fraction of radical innovation uptake in different income categories.

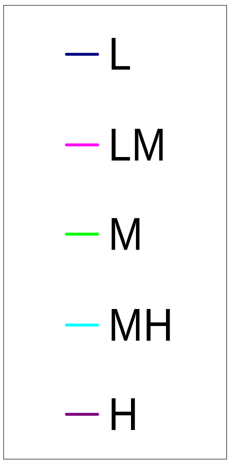


Figure A1 shows the fraction of households that invest in radical innovations (ie PV solar panels). As one would expect, it is household with high income levels that have sufficient resources to invest in radical technologies. However, there is no linear relationship between investment decisions and income levels. In four out of the six experiments, it is the medium-high income levels that invest latest in radical technologies. The reason is that medium-high income households use proportionally more energy than the lower and middle income households, but they receive far less income than the higher level income households. This means that they are buyers of credits, but they can only obtain credits after the higher income households have satisfied their needs. In other words, they use much of their income trying to sustain their energy use and have therefore less resources for investments in energy-efficient technologies.

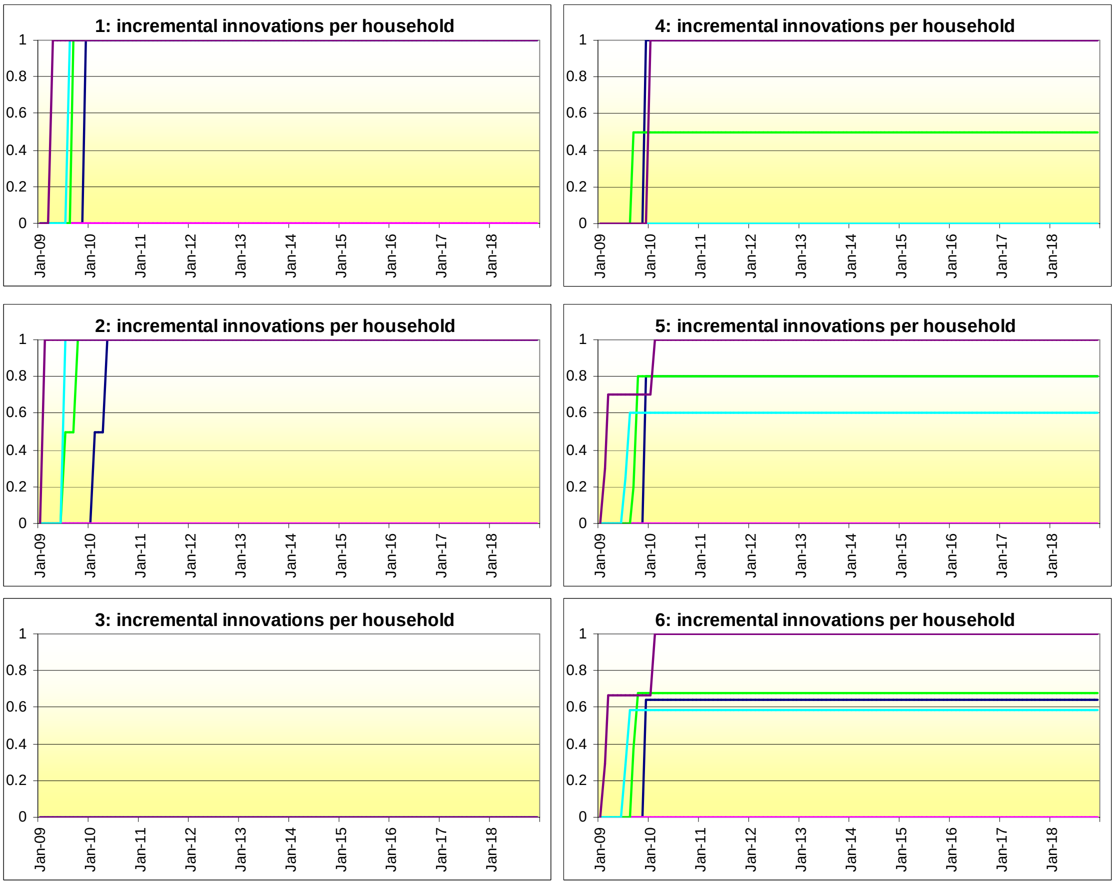


Figure A2. Fraction of incremental innovation uptake in different income categories.

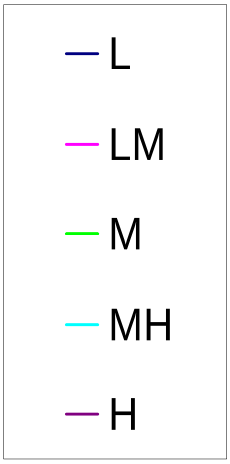


Figure A2 and figure A3 (next page) show that the uptake of incremental and marginal innovations can be explained in a more linear way. Households with higher income levels are able to invest in these technologies earlier than households with lower income levels. However, both figures show that there is actually a high uptake of both incremental and marginal innovations in the first couple of years if households would behave rational and focus on the economics of their investments. Since the model is based on empirical information, this suggests that more focus on the emissions associated with energy use would indeed benefit the uptake of these technologies under a scenario where households would focus on the economics.

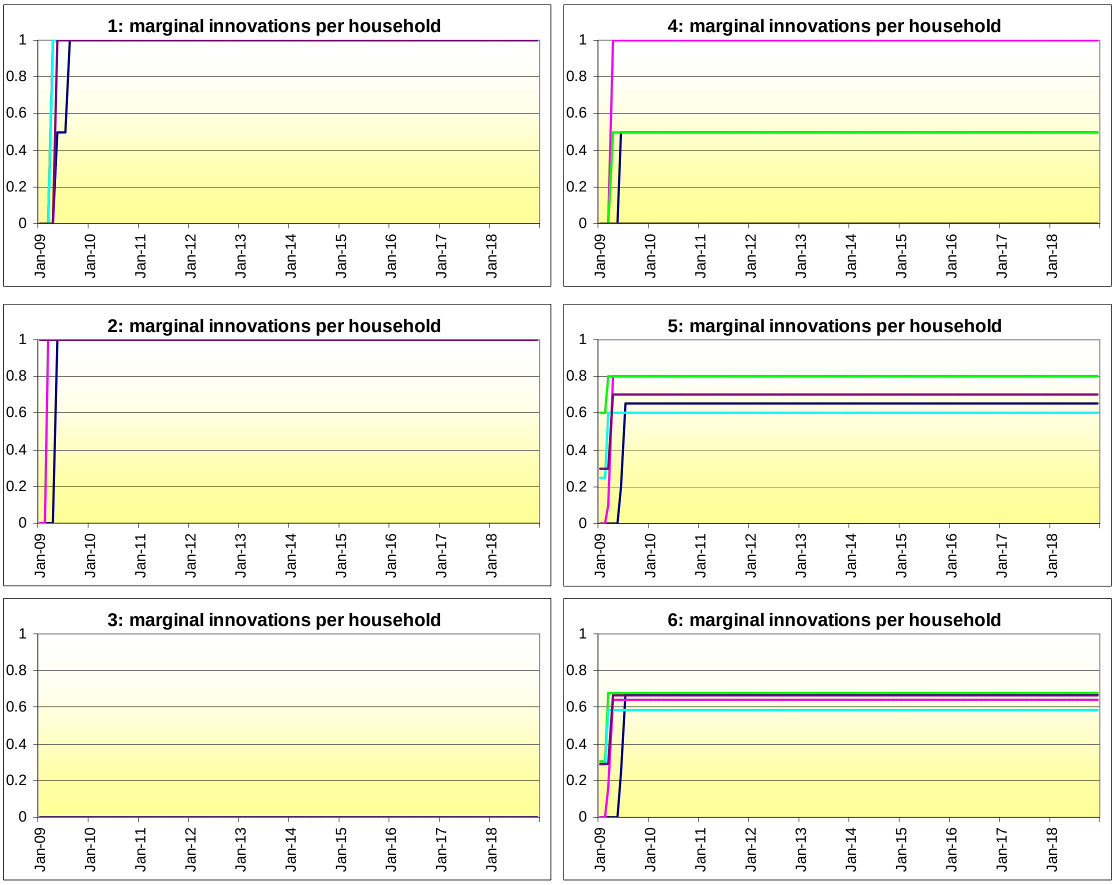


Figure A3. Fraction of marginal innovation uptake in different income categories.

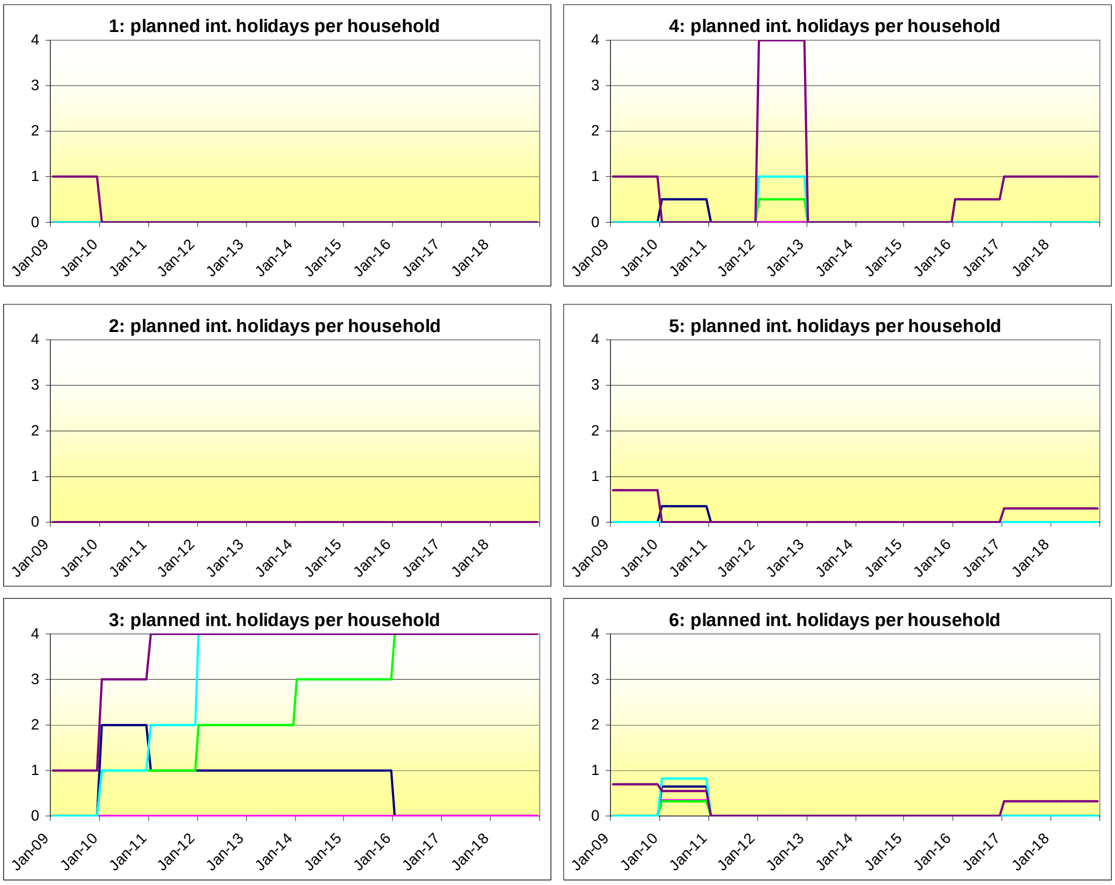


Figure A4. Average number of planned international holidays per household in different income categories.

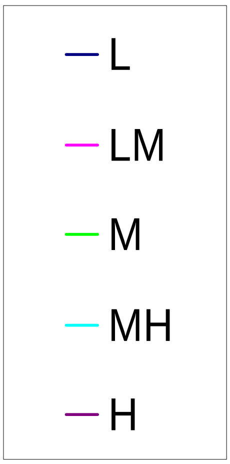


Figure A4 and figure A5 (next page) show the number of planned international and UK holidays for each of the household income categories and for each of the scenarios. It shows that under economical focused behaviour (see table 4: only go on holiday if the costs of the holiday is less than the associated carbon emissions cost), the PCT reduces the incentive to go on holiday. From this perspective, it can be concluded that PCT could have an important impact on the behaviour of households (especially international holidays). However, the results simultaneously show that households that are determined to go on holiday will remain doing so. In other words, if households do not respond to a carbon price with regard to their holiday behaviour, a PCT might result in high levels of households that cannot buy energy for heating/lighting their houses at the end of the year, since they cannot afford the carbon credits. Such behaviour would mean that the PCT has failed in achieving any behavioural change, affecting the living circumstances of many households throughout the UK. Although, as previously mentioned, each of the interpretations of behaviours is stylised and does not need to reflect reality, anyone should be aware of the possible consequences of PCT under such behaviour.

Figure A5. Average number of planned UK holidays per household in different income categories.

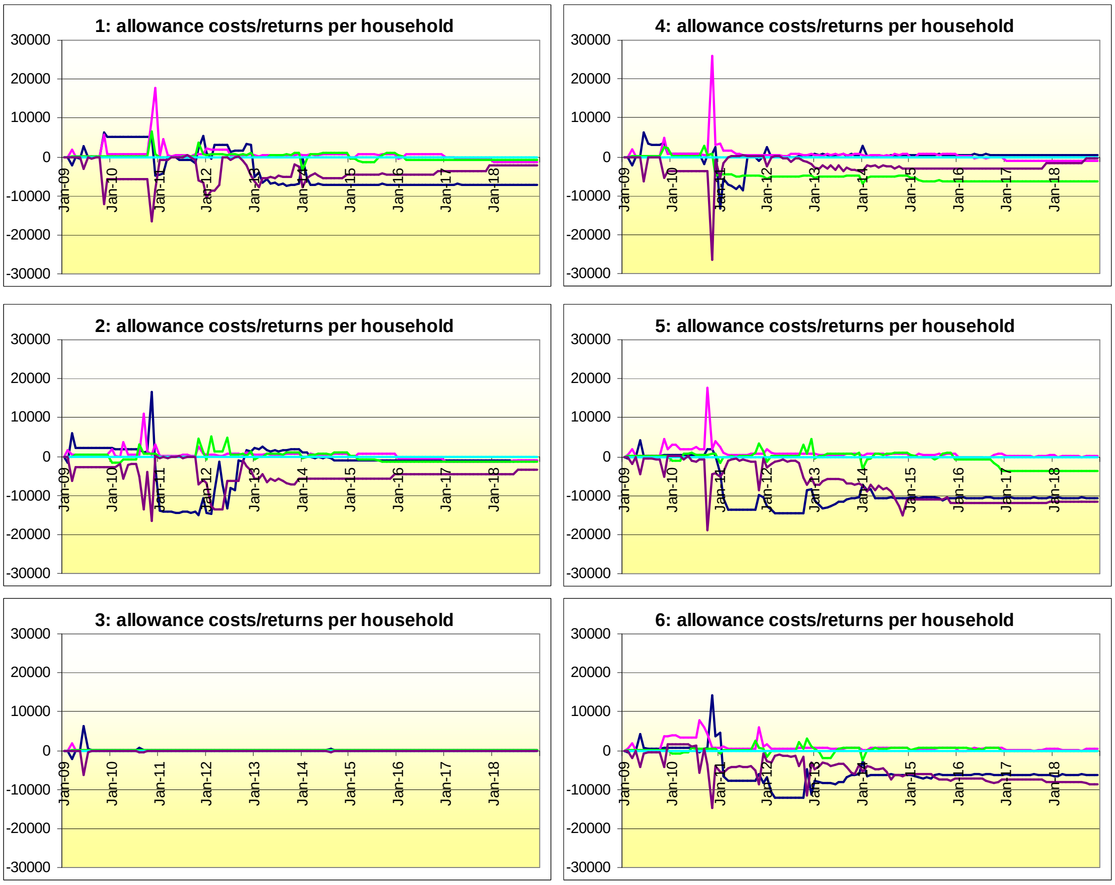


Figure A6. Average expenditure/returns (in £) on carbon credits per household in different income categories.

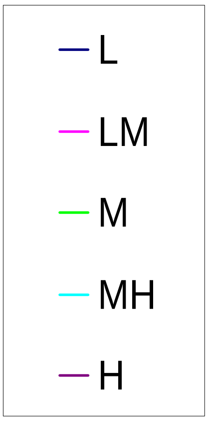


Figure A6 shows the average expenditure and returns (in £) on carbon credits per household in the different income categories. Since PCT is a closed system, the total amount of money spend on buying carbon permits is equal to the total amount of money earned by selling carbon permits. Consequently, the results show that expenditure in one household category results in income in another household income category. The results are presented as the cumulative expenditure/returns per household income category, which explains why some of the expenditure/return levels become fairly static after a couple of years. Although the individual expenditure/returns might differ for each household within a particular income category (especially in cases where they have different behaviours), these results show how different income categories are affected by the introduction of PCT. The results clearly show that there is no direct linear effect between PCT and household income levels. In other words, it is not the case that low income households receive more returns than low-middle income households which receive more returns than middle income households. Furthermore, it shows that households' earnings/expenditure levels out after a couple of years, which is the direct consequence of the assumption that there are only three technologies in which the households can invest.